Water in Nevada

A basic overview of hydrologic principles as related to America's driest State

Michael L. Strobel

Cover Photo: Susie Creek north of Carlin in the Humboldt River Basin.

Water in Nevada

A basic overview of hydrologic principles as related to America's driest State

Michael L. Strobel

Water in Nevada
A basic overview of hydrologic principles as related to America's driest State

Michael L. Strobel, Ph.D.
U.S. Geological Survey
Nevada Water Science Center
Carson City, Nevada

Technical Editors: Patricia Revitzer, Carissa Strobel, Angelia Thacker, Shannon Watermolen
Illustrations: Nancy Damar
Book Design: Shannon Watermolen

While writing the newspaper articles which were compiled to provide the text for this book, numerous people from the USGS Nevada Water Science Center have assisted in the review process. At the risk of overlooking any individual who may have helped, which I apologize for upfront, I will try to identify the people who have directly contributed to this effort. Technical reviewers of the various chapters include David Beck, David Berger, Steven Berris, Daniel Bright, Robert Burrows, Guy DeMeo, Kerry Garcia, Kimball Goddard, Keith Halford, Michael Lico, Douglas Maurer, Russell Plume, David Prudic, Donald Schaefer, Ralph Seiler, Alan Welch, and Jon Wilson. Editorial and technical assistance with illustrations, layout and processing were provided by Nancy Damar, Teresa Foglesong, Keith Kirk, Patricia Revitzer, Angelia Thacker, and Shannon Watermolen. I would like to thank Kent Harper of the Ely Times for allowing me to publish the weekly column in this newspaper and the many people in White Pine County, Nevada, who read the articles and provided feedback and questions. Most of all, I would like to thank my wife, Carissa, for reviewing most of the articles as I wrote them over the weekends, providing excellent technical feedback and editing, and always being supportive.

Preface

Over the many years that I have worked as a hydrologist with the USGS, I have had the opportunity to make numerous presentations and attend hundreds of meetings in which water issues were discussed with the general public. While it was rewarding to see that people have a strong interest in water, it also was frustrating to see people struggle to understand the concepts and the terminology used by hydrologists. The concepts rarely were difficult, but rather that hydrology, like all sciences, has its own language.

Therefore, I felt it was important to try and find a way to discuss hydrology in a way that non-hydrologists could understand. About 14 years ago, I put together a class for teaching basic hydrology principles to people with little-to-no science background. I taught this class at a couple of universities to students who needed more education in hydrology before taking advanced classes and I presented a 3–day version of the class to many different groups of non-hydrologists around the country over the next 10 years. It was rewarding to see people begin to understand and appreciate hydrology once it was presented at a level and in a fashion they could grasp.

This leads up to how and why this book was created. In 2004, I was asked to give a talk to the Tri-County Commission (Lincoln, Nye, and White Pine Counties of Nevada) in Ely, Nevada. Water issues, and mainly the potential of deportation of water from ground-water basins in these counties to southern Nevada, had become a topic of much interest to the residents of this part of Nevada. At this meeting, the State Engineer gave a talk on water law, and I gave an overview of the hydrogeology of eastern Nevada. Questions I received from the audience during and after my talk, along with numerous discussions and words of appreciation following my talk, made me realize that people in the area had a strong interest in hydrology and a need for more information that could help them better understand the water resources in their part of the State.

Not long after the talk, I met with the editor of the local newspaper, the Ely Times, and asked if he would be interested in a few columns that would discuss basic water principles and definitions for the readers in the area. He felt it was a good idea, and so I set off to write a few articles to be printed in the paper. Interest grew and I enjoyed writing the articles, so we continued putting out a column each week, and now I have done more than 50 different articles and I am still writing. Many of the articles deal with specific questions I have received from the readers, whereas others cover general topics and information.

Because of the general knowledge contained in the articles and strong public interest in having the topic of hydrology presented at a level for non-hydrologists, it was felt that these articles should be combined into a single document and offered for a wider distribution. I was approached by representatives from the State Engineer's office, SNWA, and NWRA about putting this book together. However, many of the articles were written for a newspaper audience in Ely, Nevada, and not for a wide distribution. Likewise, some of the topics I wrote about in the newspaper have a current interest, such as on-going studies or local events, which may not be appropriate for a book that might be around for a few years. Therefore, I have selected articles from the newspaper column that have more of a general interest and rewrote some of the information to make it more applicable to all of Nevada.

Writing the column for the Ely Times each week was (and still is) much fun for me. I enjoy discussing hydrology with people and I appreciate the comments and questions I receive. Hopefully, this book will be useful to the readers by increasing their interest and knowledge in hydrology.

The one thing I would like to make clear concerning this book is that I write about hydrology from a completely neutral position. The organization I work for, the USGS, and my own personal convictions are the same in that the information presented and the research completed are intended to be entirely impartial and without bias. Many people wish to use science to push a specific agenda or to justify a specific cause. That is fine for those individuals or groups, and I certainly understand that arming oneself with knowledge is a powerful tool. But from my perspective, and the perspective of this book, all the information provided is for general knowledge and there is no intention to show bias to any one cause or agenda. One of my favorite quotes, and I don't remember the author, is that "the purpose of education is to replace an empty mind with an open mind." There are many sides and many perspectives to every issue, and maybe this book will help in understanding why the issues are important, and maybe even why people see them from different points of view. I hope this book provides some education and that the readers use the knowledge to understand the complex water issues that face Nevada now and in the coming years.

— Michael L. Strobel, Ph.D.
USGS

Table of Contents

CHAPTER 1
Water Definitions 1

CHAPTER 2
Water Budgets 7

CHAPTER 3
Measuring Precipitation 9

CHAPTER 4
Droughts 13

CHAPTER 5
Surface Water and Hydrographs 17

CHAPTER 6
Making Streamflow Measurements 21

CHAPTER 7
Porosity 25

CHAPTER 8
Aquifers and Confining Units 27

CHAPTER 9
Springs 31

CHAPTER 10
Unsaturated Zone 33

CHAPTER 11
Ground-Water Flow 35

CHAPTER 12
Hydraulic Conductivity 37

CHAPTER 13
Well Construction 39

CHAPTER 14
Making a Well Measurement 43

CHAPTER 15
Cone of Depression 47

CHAPTER 16
Aquifer Tests 51

CHAPTER 17
Evapotranspiration 53

CHAPTER 18
Geology of Eastern Nevada and the Occurrence of Ground Water in the Carbonate Aquifer System 55

CHAPTER 19
Alluvial Basins 57

CHAPTER 20
Geophysics 59

CHAPTER 21
Water Quality 61

CHAPTER 22
Contamination 63

CHAPTER 23
Isotopes 67

CHAPTER 24
Radioactive Isotopes 69

CHAPTER 25
Water Use 71

CHAPTER 26
Water Sustainability 73

CHAPTER 27
Dowsing or Water Witching 75

Chapter 28
Your Questions Answered 77

Chapter 29
Lake Tahoe 83

Chapter 30
Lake Mead 87

Chapter 31
Great Basin National Park 91

Chapter 32
Wetlands 95

Chapter 33
Terminal Lakes 97

Chapter 34
Floods 101

Chapter 35
Nevada Water Resources Association 105

Chapter 36
The U.S. Geological Survey 107

Chapter 37
References Cited 111

Acronyms and abbreviations used in this document

°	Degree
BLM	Bureau of Land Management
BOR	Bureau of Reclamation
DCNR	Nevada Department of Conservation and Natural Resources
DRI	Desert Research Institute
ET	Evapotranspiration
F	Fahrenheit
GIS	Geographic Information System
GPS	Global Positioning System
MCL	Maximum contaminant level
MPH	Miles per hour
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NRCS	Natural Resources Conservation Service
NWRA	Nevada Water Resources Association
PVC	Polyvinyl chloride
SNWA	Southern Nevada Water Authority
U.S.	United States
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

Chapter 1

Water Definitions

In many hydrology textbooks, the glossary of terms usually is an appendix in the back of the book. The glossary in this book is up front because people need to be familiar with the terminology if they wish to understand the rest of the text. It isn't expected that everyone grasp each of these terms from the short definitions provided here, but this chapter can be a reference to come back to during later chapters.

As mentioned in the preface, science, and in this case, hydrology, has its own language. The concepts are often quite simple, but the scientific terms can confuse and inhibit some people from understanding a water discussion. For example, the term "ET" is used a lot. No, it is not referring to a little alien in a science fiction movie; it refers to "evapotranspiration", which is a very important component in a "hydrologic budget".

Therefore, this is a list of some of the more common hydrologic terms. You can refer back to this chapter if a term is used that may not be familiar to you later in the book. The goal was to describe each term in simple words, but it was important to make sure each was scientifically accurate. Many of the definitions come from years of teaching the subject, using a variety of sources of information, and scanning through numerous USGS publications. The most important references used are Heath (1989) and information contained in hydrology textbooks such as Fetter (1988) and Freeze and Cherry (1979).

Adsorption
: Attraction of fluids, such as water and contaminants, to rocks and sediments.

Alluvium
: Sediments deposited by rivers. These sediments typically fill valleys between mountain ranges.

Aquifer
: Rock or sediment that is saturated and can transmit sufficient water to supply wells.

Aquifer test
: A test performed by pumping a well for a certain length of time and observing change in the elevation of water level in the aquifer (amount of change in the water levels in observation wells).

Aquitard
: A geologic layer that has a low permeability and can transmit water slowly to adjacent aquifers.

Artificial recharge
: Adding water to an aquifer through injection to wells or by adding water to ponds.

Baseflow
: The portion of streamflow that comes from ground-water discharge.

Capillary fringe
: Saturated area above the water table where water is drawn upward by capillary action (water resists the pull of gravity due to attraction between water molecules and surrounding sediment).

Confined aquifer
: An aquifer that is overlain by a layer of low-permeable material (such as clay or fine silt) that inhibits the movement of water through it.

Confining unit
The geologic layer of low permeability that is adjacent to an aquifer and prohibits flow into and out of the aquifer (can be either above or below an aquifer).

Connate water
Deep water in an aquifer that has been out of contact with the atmosphere for a long period of time.

Contaminant
An addition to water that makes it unusable for a specific use.

Darcy's Law
Equation used to calculate properties of ground-water flow.

Discharge
Volume of water flowing in a stream or moving through an aquifer at some specific time. For ground water, discharge often is used to describe water leaving a system (due to ET, baseflow, and ground-water flow out of a basin). Discharge is often abbreviated as Q.

Drainage basin
Area in which surface runoff (precipitation and snowmelt) drains into a single surface-water body.

Drainage divide
Boundary line (highest elevation) separating drainage basins.

Drawdown
Lowering of water level or potentiometric surface by pumping a well.

Equipotential line
A line connecting points of equal water levels or potential head.

Evaporation
Process of water transforming from liquid to vapor.

Evapotranspiration
Combination of evaporation and transpiration from plants. Evapotranspiration often is abbreviated as "ET".

Finite-difference model
A digital computer simulation which divides an area based on a grid of rectangular cells and attempts to mimic actual conditions.

Flow net
A set of intersecting equipotential lines and flow lines used to indicate directions and gradients of ground-water flow.

Gaining stream
A stream whose flow is increasing due to inflow from ground water.

Ground water
Water held in spaces, pores, and openings in rocks and sediments beneath the surface of the Earth. Ground water often is abbreviated as "GW".

Ground-water mining
Withdrawing ground water at a rate exceeding natural recharge.

Hardness
Amount of calcium, magnesium, and iron in water. Hardness makes it difficult for soap to form lather.

Head
Water level in an unconfined aquifer or amount of pressure (potential) in a confined aquifer. Head typically is the measure of elevation of a water level in a well open to either a confined or unconfined aquifer. Often referred to as "hydraulic head".

Hydraulic conductivity
Rate at which water can move through a permeable material. Hydraulic conductivity is different from permeability (see definition below) because hydraulic conductivity considers the properties of the medium and the properties of the fluid (viscosity and density). Hydraulic conductivity often is abbreviated as "K".

Hydraulic gradient
Change in head over distance, usually measured as water levels in wells and shown as difference in heads over that distance. Hydraulic gradient often is abbreviated as dh/dl.

Infiltration
Movement of water from the Earth's surface into the ground.

Karst
Openings in rocks, typically in carbonate (limestone) rocks, caused by dissolution of the rock. Karst is most often referred to as caves and caverns.

Losing stream
A stream where flow is decreasing due to water infiltration into the ground.

Model
A representation of the real world. Hydrologists often use various models for explaining a system. Conceptual models try to explain what variables or conditions affect the inputs and outputs of a system (where the water is going). Numerical or digital models try to quantify those variables or conditions.

Model calibration
Process of changing values in a model, such as hydraulic conductivity, in order to match the model to known variables, such as water levels.

Observation well
A well used to observe water levels or heads in aquifers. These wells can be of various diameters and also can be used to collect water samples.

Perched aquifer
Ground water that is trapped or "perched" above the water table due to a clay layer (or zone of low permeability) separating the two layers.

Permeability
Rate at which water can move through a material. Unlike hydraulic conductivity, permeability only considers the properties of the medium and not the properties of the fluid.

Phreatophyte
A plant that has a taproot extending to the water table. Indicates a relatively shallow water table.

Porosity
Ratio of volume of void spaces (pores) to total volume of a sediment or rock. Porosity can affect the amount of water that can be held by the sediment or rock.

Potentiometric surface
Surface to which water would rise in a well open to a particular aquifer. In a confined aquifer, the potentiometric surface is above the top of the aquifer.

Recharge
Usually refers to water entering a ground-water system. Infiltration of precipitation and streamflow often are components of recharge.

Runoff
Total amount of water flowing in a stream resulting from rainfall or snowmelt.

Safe yield

Refers to the amount of water that can be withdrawn from an aquifer without impairing water quality or creating unacceptable effects from lowering water levels. Safe yield is the balance between water withdrawn and recharge or leakage from surrounding units. The terms “safe yield” and “perennial yield” are open to various interpretations and remain a point of contention between water professionals.

Semiconfined aquifer

An aquifer where the confining unit allows a certain amount of discharge and recharge to occur. Also referred to as a leaky confined aquifer.

Specific yield

Ratio of the volume of water either sediments or rocks will produce due to gravity drainage to the total volume of the sediments or rocks. In unconfined aquifers, specific yield represents how much water will come out of storage during pumping.

Specific storage

This term refers to how much water will go into or out of a porous medium (such as an aquifer) per unit volume of the medium per unit change in head. In other words, if you pump an aquifer and lower the head, specific storage is the amount of water that will come from the aquifer due to the change in head. Specific storage is often abbreviated as “Ss”.

Spring

Point of ground-water discharge to the surface. Many different types of springs exist depending on the type of feature that causes the spring. For example, a “water table spring” is where the water table intersects the land surface (often on a steep slope), a “fracture spring” occurs where a bedrock fracture intersects land surface, and a “bedding spring” is where water runs along the top of a geologic bed and discharges to the surface where the bed outcrops.

Storativity

The volume of water that an aquifer can take in or release per unit surface area of the aquifer per unit change in head. This is specific storage times the aquifer thickness. Storativity often is abbreviated as “S”.

Transmissivity

Rate of water movement through a unit width or thickness of aquifer. Transmissivity often is abbreviated as “T”. Transmissivity is equal to hydraulic conductivity times aquifer thickness. Transmissivity is essentially a measure of the aquifer’s ability to transmit water.

Transpiration

Process of plants taking up ground water and soil moisture through their roots and emitting water vapor through their leaves.

Unconfined aquifer

Aquifer with direct connection to the atmosphere (no confining unit between aquifer and the Earth’s surface). Water level in an unconfined aquifer is referred to as the water table.

Vadose zone

Zone of unsaturated rock or sediments above the water table.

Water budget

The summary of recharge and discharge components to either a drainage basin or an aquifer. Recharge minus discharge should equal zero, plus or minus changes in storage.

Water table

The upper limit of fully saturated ground that is in equilibrium with the atmosphere in an unconfined aquifer.

Well casing

Pipe (usually steel or PVC plastic) used to keep well open through sediments and unstable rock.

Well log

A log (list) of geologic material encountered during well construction, listed from land surface to the bottom of the well.

Well screen

Well casing with slots or holes to allow water to enter the well while keeping sediment out. Typically used in unconsolidated sediments and unstable rocks.

Xerophyte

Desert plant that requires minimal amounts of water and has an extensive shallow root system.

MX Well in southern Railroad Valley near Nyala. Photograph by D.H. Schaefer, 2005.

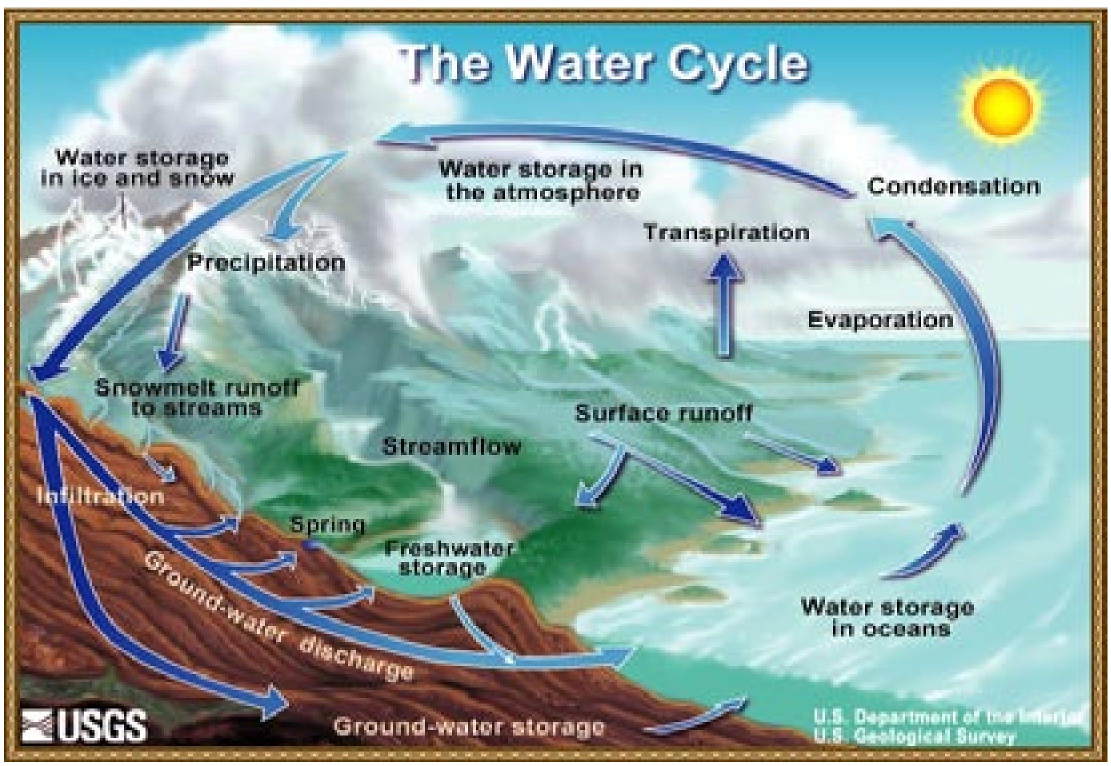
Chapter 2

Water Budgets

When trying to understand some aspects of hydrology, whether it is ground-water flow, springs, surface water, evaporation, water quality, or any other topic, one needs to first look at the whole system. In hydrology, all topics are dependent on each other.

For example, precipitation distribution affects runoff and ground-water recharge. Recharge affects ground-water levels in shallow aquifers. Ground-water levels can affect springs and contributions to surface water. Precipitation, geology, ground-water levels, and surface water can affect water quality, and these interactions and relations continue throughout a hydrologic system.

The term scientists use for the overall system is the Water Cycle. On a global scale, the water cycle can be simplified into a series of steps that a particle of water would follow from one natural state to another. The following diagram illustrates this process.



In this cycle, a water particle gets evaporated from the ocean. The particle contributes to cloud formation as condensation. The clouds move over the land surface, become cooled, and the water particle falls to the land surface as either rain or snow. The runoff or snowmelt either flows downgradient as surface water or infiltrates the ground and becomes ground water. Both the surface water and ground water ultimately discharge to the oceans, and the cycle starts all over again. Of course, this is a gross simplification of the real world water cycle, and water particles actually can follow a multitude of pathways that are all part of the water cycle.

For example, water that reaches the Earth as rainfall or snowfall can be evaporated back into the atmosphere before it has the chance to infiltrate or become runoff. Various interactions occur between ground water and surface water; water that infiltrates and becomes ground water can later discharge to the surface as springs or baseflow to streams and possibly reenter the ground-water system later in stream-loss areas or become evaporated and reenter the atmosphere. So water can take many different paths in the water cycle, but the overall concept is valid, that being water is always changing from one state to another, and the process is continuous.

This brings us to a discussion about water budgets. A water budget is a lot like a budget you might keep for your personal finances. Many inputs and outputs can affect the budget.

Let's look at a single basin in order to better understand water budgets. In a basin, certain natural water inputs exist. These include precipitation (rainfall and snowfall) and inflows by streams and ground water from other basins upgradient. The water outputs from the basin include ET (evaporation of surface water and transpiration from vegetation using water) and streamflow and ground-water flow out of the basin. These natural factors can affect affect a basin's water budget.

Of course, human influence such as ground-water pumpage, artificial recharge, manmade lakes and reservoirs, vegetation removal, surface paving of open fields, irrigation of crops, etc. can affect the natural water budget of a basin.

One way to look at water budgets is as a simple equation:

Water Budget = Inputs – Outputs +/- Changes in Storage

In a balanced system, the inputs would equal the outputs in quantity. However, it's the changes in storage that raise concerns. Going back to the personal finance example, if this was your savings account, your account would be in balance (no change) if your income equaled your bills paid each month. If you lower your income, not all the bills can be paid without dipping into savings. Likewise, if you get a nice promotion, then your bills get paid and your savings account grows.

The increase or decrease in your balance is the same as changes in storage in the water budget. If the precipitation and inflows of surface water and ground water equal the outputs from ET and outflows of surface water and ground water, then the water budget is balanced and storage does not change. However, if one component is changed, then the system is no longer in balance and storage changes.

Examples of what can change the storage include both natural and human impacts. During drought, precipitation decreases, which results in less input into the water budget for a particular basin. With less precipitation, it's probable that ground-water levels will decline. The ground-water level decline results in a change in water storage for the basin because less water is now held in the aquifers. Likewise, if climatic conditions changed and above-normal precipitation occurred for a few years, then more recharge to the aquifers would result, which would be an increase in basin water storage.

Human impacts, such as wells installed in aquifers in a basin for either public supply or irrigation, also could result in changes in storage because the balance of the water budget was altered. Often, water pumped for human consumption is transported out of the basin, so this water is effectively a loss in storage. Water pumped for irrigation usually stays within a particular basin, but much of that water is lost to ET when applied to surface crops. Therefore, the output side of the equation is increased with this activity and it results in a change in storage.

One thing to consider when looking at water budgets is the effect of scale. Many potential impacts on a water budget, such as annual variations in precipitation or ground-water pumpage for domestic uses, are so small compared to the total size of the basin and the ground-water system that the effects are practically unnoticeable. Also, so much water in Nevada is lost to ET that many changes in the inputs and outputs of a water budget are masked by slight changes in the amount of water lost to the atmosphere.

Because of the large scale of the basins and the small scale of the impacts, many of these effects are too small to measure. Also, because so much water is stored in aquifers in eastern Nevada, even large-scale ground-water pumpage might not be detectable in the short term (years or decades) because the water is coming out of storage and not directly from the inputs and outputs. In other words, the effects on springs, lake levels, and vegetation might not be detectable for a long time.

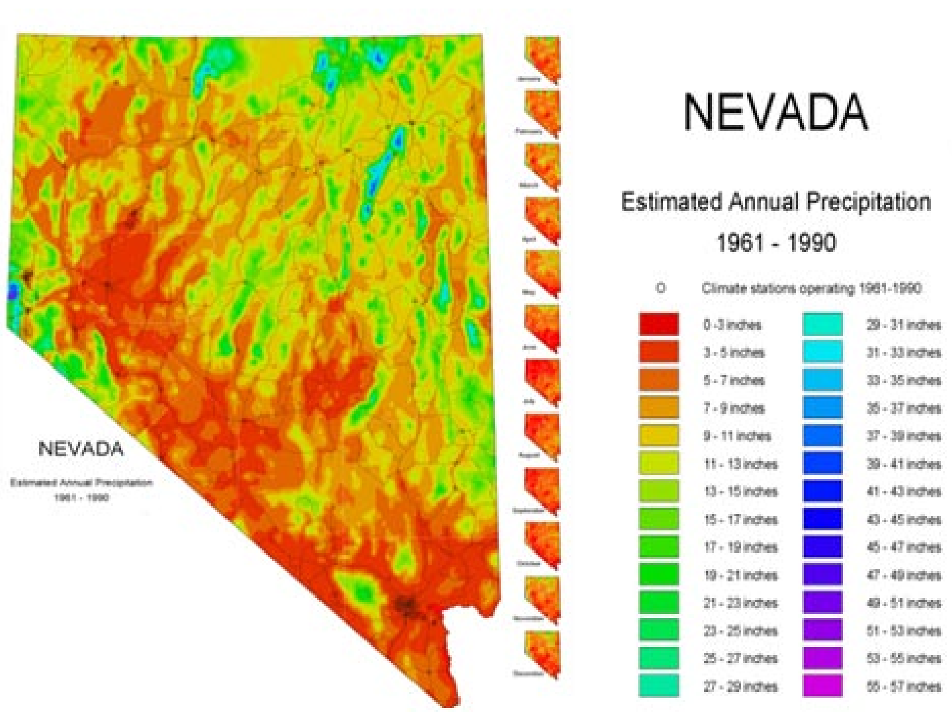
Chapter 3

Measuring Precipitation

Nevada has often been referred to as the driest State in the Union. Based on average annual precipitation, this is a true statement. In general, Nevada receives less than 10 inches of precipitation over an average year (based on records for the period 1961–1990). In times of drought, decreases in the annual precipitation have put additional stress on our water resources.

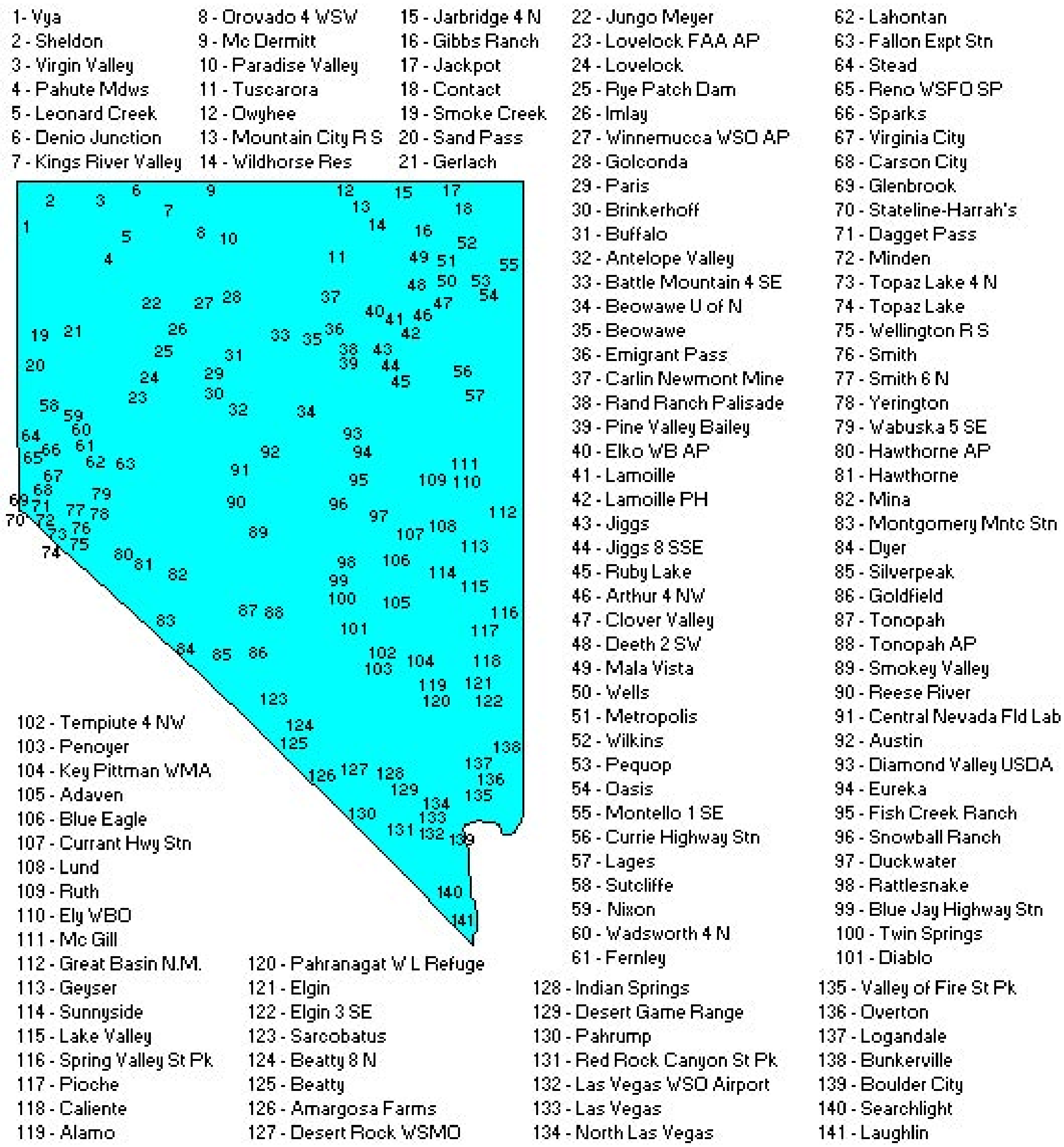
When referring to precipitation, it includes snowfall and rainfall. In reality, snowfall and rainfall in the mountains of Nevada account for most of the total precipitation for the State. The reason for this is that higher elevations in the mountains cause moving air masses to rise and become cooler. As the air cools, it no longer can hold as much moisture as it could in lower, warmer elevations and the moisture condenses. The result is precipitation on the mountains. Measuring precipitation in Nevada is an important science because many of our estimates of water budgets are based on this information.

The map below shows a graphic representation of precipitation distribution for Nevada. The locations of major mountain ranges can be seen by the distribution of the precipitation.



Source: This figure was compiled from estimated annual precipitation values calculated by the PRISM Climate Mapping Program at Oregon State University. The small side maps show estimated precipitation in each month. Precipitation values are interpolated from estimates made on a 1 kilometer grid. (Nevada Department of Conservation and Natural Resources, 2004).

Precipitation is measured at various sites across Nevada. Many sites are at airports and public facilities, but some sites are on private lands. In addition to precipitation, other weather data, such as temperature, wind speeds, wind directions, etc., also are recorded. These stations typically use mounted rain gages that are read regularly so that each precipitation event is recorded (date, time, and amount). A distribution of these stations in Nevada is shown below:



Source: Nevada Climate Summaries Imagemap: National Resources Conservation Service, National Water and Climate Center (Desert Research Institute, 2004).

Another source of precipitation data in Nevada is the National Trends Network (NTN), which is operated by the USGS. Two active gages are in Nevada which consist of large bucket collectors with sensors in the lids. As soon as the sensors detect moisture, the lids automatically open and collect the precipitation. These sites are visited every week and the amount of water collected as precipitation is determined by measuring the weight of the water in the collector. In addition to water volume, samples are collected and measured for chemistry (to determine what is being deposited from the atmosphere).

One more source of precipitation data in Nevada are high-altitude bulk precipitation stations. These are towers (around 12 feet tall), made of aluminum, that collect rainfall and snowfall throughout the year. The towers are placed at high elevations in the mountains in order to collect precipitation data in these remote locations. The stations are measured twice a year (typically in May and October). In addition to the precipitation collected at the towers, these stations contain mineral oil to prevent evaporation from the collectors and antifreeze to reduce the chance of freezing during the winter months.

High-altitude precipitation gage in Kyle Canyon, Mt. Charleston, Nevada. Photograph by J.W. Wilson, USGS.


Thunderstorms over Battle Mountain. Photograph by R.W. Plume, USGS.

Chapter 4

Droughts

Drought can be defined as "a period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance in the affected areas" (American Meteorology Society, 1959). In other words, drought is a period without rain or snow where normal conditions are changed, such as a lack of soil moisture or reductions in water supplies (water tables, lake levels, streamflow, etc.). Often, we see short-term events as turning points in weather patterns, but we need to step back and look at the bigger picture. A week of cold weather in June does not prove global warming is false, just as a week of rain in October does not define the end of the drought.

Nevada is the driest State in the Union. With this in mind, one might argue that the people in Nevada live with drought all the time. While it certainly is dry in Nevada, the people still depend on a level of annual precipitation to keep their aquifers replenished and their streams flowing so that they can irrigate crops and fields. Often, winter snow pack in the mountains provides the precipitation to maintain the water balance for the rest of the year. Reductions in that snow pack can mean drought conditions for the valleys.

So, can drought be defined by a lack of precipitation, or a decline in soil moisture, or a drop in streamflow, or when water restrictions are put in place on various cities and areas? The answer is yes to all four. Drought can be defined in reference to meteorological, agricultural, hydrological, or socioeconomical standards (National Oceanic and Atmospheric Administration, 2005).

Meteorological drought refers to a period when the amount of precipitation is below normal. This standard can be highly variable from one location to another. For example, let's say that rainfall in Carson City was below normal for a year. However, the precipitation in the Sierra Nevada adjacent to Carson City was at or above normal for the same year. By definition, Carson City would be in a drought, while the nearby mountains are not. The reality is that much of the moisture from the mountain precipitation probably will flow into the valley and therefore supply sufficient water for crops and aquifer recharge, but the valley is still considered under a meteorological drought.

Agricultural drought refers to conditions when soil moisture is insufficient to meet crops needs. Because crops in Nevada depend on irrigation for survival, this definition does not apply to Nevada by itself. However, because drought can affect hydrological conditions, which supply water for irrigation, agricultural drought can be related to hydrological drought. In many places in the Eastern U.S. where irrigation is not used, agricultural drought is a very serious subject.

Hydrological drought refers to conditions when snowpack, lake levels, streamflow, and ground-water levels are below normal. In a desert environment like Nevada, this type of drought condition is the most serious. Declines in Nevada's water supplies can affect the ability to irrigate crops, maintain habitat for animals (wild and domestic), and provide for human needs.

Socioeconomic drought is when water shortages begin to affect the people. In some cases, a deficit of precipitation can have little effect on people if there are sufficient supplies to keep things as "business as usual." A lot of this depends on the amount of water in storage and the length of time of the drought. In other cases, a deficit in precipitation (and related declines in water supplies and soil moisture) can have huge socioeconomic effects; for instance, during the "Dust Bowl" era, people were displaced and ways of life changed. When drought causes a change in lifestyle or business practices, then it has a socioeconomic effect.

Drought typically is measured using a number of different indices. One is the Percent of Normal, which is a measure of precipitation compared to "normal precipitation," typically considered the 30-year average. Another index is the Standardized Precipitation Index (SPI) which is based on the probability of precipitation for any time scale and can provide an early warning of drought and assess drought severity. The Palmer Drought Severity Index (PDSI) is a meteorological drought index based on soil moisture. The Crop Moisture Index (CMI) is similar to the Palmer Index and uses moisture supply as required by certain crops. The Surface Water Supply Index (SWSI) is calculated by river basin and is based on snowpack, streamflow, precipitation, and reservoir storage. The Reclamation Drought Index (RDI) is calculated for river basins and uses the same parameters as SWSI, plus temperature. Most drought observers use one or more of these indices to evaluate drought conditions.

The severity of drought can depend on where you live. In parts of the country where rainfall is critical for crop production and quality of life (lawns, golf courses, etc.), a few weeks without rain can cause great concern. In the Southwest U.S., where rainfall is less common, it might take prolonged periods (months or even years) before people feel the effects of drought. For example, people in southern Nevada depend on Lake Mead for their water supply. Lake levels depend on flow from the Colorado River, which is supplied mainly from precipitation in the upper basin (Colorado, Wyoming, and Utah). A prolonged drought in the Western U.S. might not have immediate effects on water supplies from Lake Mead, but over time, the effects would be cumulative and become more apparent to the general public.

Declines in water levels in Lake Mead create a "bathtub ring" effect as rocks that were previously submerged became exposed along the lake edge, September 2004. Photographs by Ryan Rowland, USGS.

One effect of drought that we all can relate to is the increase in forest fires. Fire potential increases as conditions become drier. During a drought in California around 1970, fires accounted for tens of millions of dollars in losses. The drought between 1984 and 1988 had huge effects on agricultural production. During this period, over 4 million acres of forest burned in the Northwest and over half of Yellowstone National Park, or about 2 million acres, was affected by a huge forest fire.

The drought of the 1930s lasted up to 7 years in some parts of the country and resulted in a mass migration of people from the Great Plains. The cost of losses related to the 1987–89 drought in the U.S. was estimated to be as high as $39 billion. As populations continue to grow, the effects of droughts on humans also will increase.

Scientists have been able to examine climate conditions that existed prior to recorded history in the Western U.S. by using paleoclimate data. These data consist of climate conditions recorded in tree rings, lake sediments, ice cores, and other features that are affected by changes in the environment. Tree ring records are abundant for the last few hundred years, and in some cases hold records for the last 2,000 years. Lake sediments and ice cores can extend even further back, often many thousands of years. The paleoclimate data indicate that many past droughts appear to have been much worse than those experienced during the last 100 years, both in duration and intensity.

In conclusion, droughts are naturally occurring weather patterns that result in a water deficit for an area. The effects of drought on humans relates to reduced water supplies, wells going dry or reduced well production, reduced soil moisture, stresses on the ecological system, increased fire potential, reduced crop production, and often water rationing. Droughts have occurred throughout time, but no one can accurately predict how intense a drought will be or how long it will last. Like the weather, all we can do is prepare for what might come and try to minimize the impacts on our lives.


Amargosa River near the California-Nevada state line.

Chapter 5

Surface Water and Hydrographs

Surface water refers to any water overlying land surface. This can include oceans, rivers, streams, creeks, lakes, ponds, wetlands, and puddles. This even includes sheet flow and runoff associated with heavy rainstorms. Springs are another example of surface water, but the topic of springs will be the focus in a later chapter.

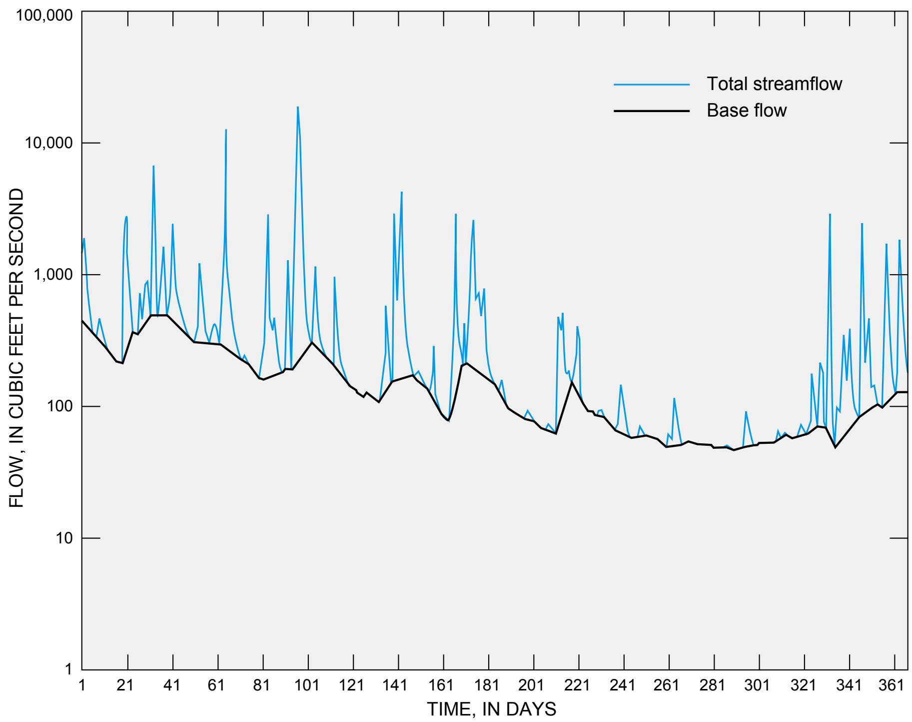
Many people view surface water as a resource separate from ground water. In some situations, this is true, but typically there is a connection between surface water and ground water and they really are part of the same system. Generally, many surface-water bodies are expressions of where the water table intersects the land surface, such as in many of the lakes and streams that occur in the valleys of Nevada. Often, increases and decreases in stage (elevation of water levels) in lakes and streams relates closely to similar changes in the water table. Thus, a lowering of the water table can result in a decline in lake and stream stage, and in some cases, the drying up of these features.

So, how do surface-water bodies form? A simple approach would be to look at the process of Horton overland flow (Horton, 1933; 1940). This process describes three stages where rainfall first infiltrates the land surface. As soils become saturated, the water begins to puddle in depressions. This is followed by puddles becoming filled and overflowing into surface flow. This surface flow will run downhill due to gravity and usually through low areas, such as valleys and channels. The term used for the surface flow of rainfall and/or snowmelt is runoff.

Stella Lake, Great Basin National Park. Photograph by D.A. Beck, USGS.

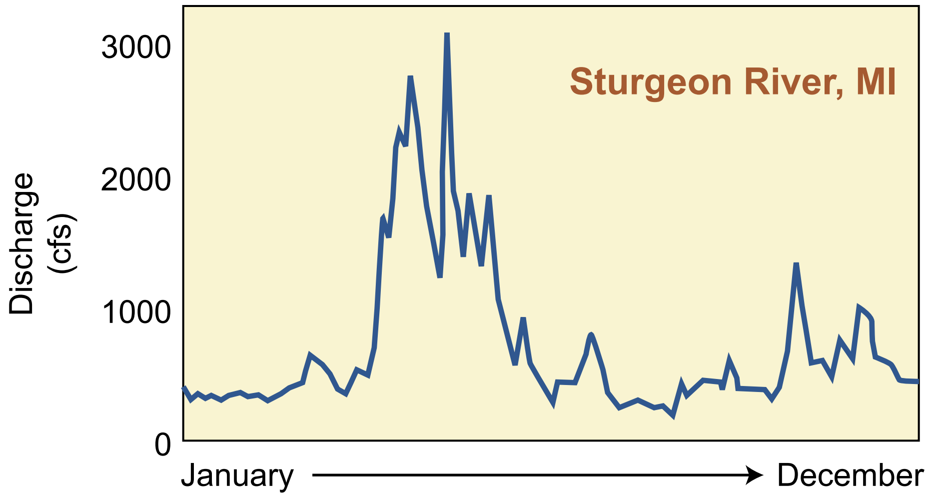
As previously mentioned, some of the water on the surface from rainfall or snowmelt infiltrates into the ground and becomes either soil moisture, held in the pore spaces above the water table, or reaches the water table and becomes ground water. If the water table intersects the land surface along a valley or channel, then the ground water can contribute to the streamflow. This contribution of ground water is called baseflow. Baseflow is what keeps streams flowing during periods in between storm events. So, some of the precipitation contributes directly to streams and lakes as runoff and some of the precipitation flows along a different path and contributes to these surface-water features after traveling through the subsurface (baseflow).

Streamflow and lake levels can be expressed graphically using hydrographs. A hydrograph is a plot of water versus time. For example, a hydrograph, as shown below, can show changes in streamflow versus time. Similarly, hydrographs can be used to show lake levels versus time and ground-water levels versus time. Hydrologists use hydrographs to help understand how lakes, streams, and ground water change with various impacts, such as storm events and droughts. In the hydrograph below, the amount of water from runoff (directly from precipitation and snowmelt) and the amount of water from ground-water discharge to the stream are shown.

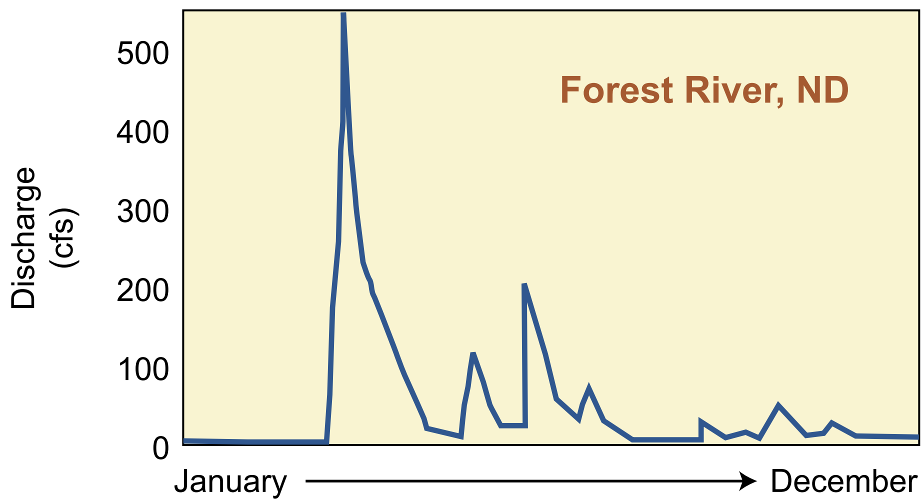


Streamflow hydrograph showing estimated baseflow (Winter and others, 1998).

Hydrographs also are useful for showing how local conditions, such as geology, slopes, vegetation cover, and other factors, affect streamflow following rain and snowmelt events. On the following page are two examples. In the first example (Sturgeon River, Michigan), the peaks in the hydrograph are wide, which indicates that a lot of the water from precipitation and snowmelt goes into the ground and gets released to the stream over time.



Streamflow hydrograph for Sturgeon River, MI (Winter and others, 1998).



Streamflow hydrograph for Forest River, ND (Winter and others, 1998).

The second example (Forest River, North Dakota) is from an area that has very low permeability, so the water from rainfall and snowmelt gets into the stream quickly (does not infiltrate into the ground) and produces narrow peaks in the hydrograph. This is because the land surface is frozen during parts of the year and also because the geology at the surface is mostly clay, which does not allow water to infiltrate readily. The annual snowmelt is very apparent in this hydrograph.

Many other factors affect the shape of hydrographs and hydrologists use hydrographs as a tool to better understand how water moves in particular locations.


Confluence of Baker and Lehman Creeks, Eastern Nevada. Photograph by D.A. Beck, USGS.

Chapter 6

Making Streamflow Measurements

You may have seen a scientist standing in a stream, holding a measuring rod and taking notes. Or you may have driven past a small gage house near a river or adjacent to a bridge. These are ways that scientists measure how much water is flowing in rivers.

It is important to understand streamflow for a number of reasons. As mentioned in previous chapters, scientists use streamflow to help estimate recharge and discharge to the ground-water system. Changes in streamflow often are related to climatic variations, such as seasons and droughts. Streamflow can be used to estimate precipitation volumes in some basins. And streamflow measurements help agencies such as the National Weather Service understand climate patterns and assess the risk of floods. These are just some of the many reasons why measuring streamflow is important.

USGS hydrologist, Tim Rowe, measuring streamflow.

The purpose of making a streamflow measurement is to assess the discharge of a stream. Discharge is the amount (volume) of water moving past some point over a given period of time. Streamflow is typically measured in cubic feet per second (cfs). For example, if a stream has a discharge measurement of 15 cfs, this means that 15 cubic feet (about 112 gallons) of water is flowing past that section of the stream channel each second.

To measure streamflow, one first needs to measure the cross section of the stream channel and the velocity (speed) of the water flow. Each of these will be discussed separately and then, how they relate to each other.

The cross section of the stream channel is the width of the stream multiplied by the depth of the stream at a particular measuring location. Obviously, stream widths and depths vary greatly along any stream channel. This is why scientists try to measure streamflow at the same location each time. The stream channel is not a rectangle, and the bottom varies as one crosses a stream. Because of this, it is important to measure the depth of water at many points across a stream in order to get an accurate profile of the channel bottom.

The stream velocity is the measure of how fast the water is moving past a point. One can get an idea of how fast a stream is flowing by throwing a stick into the water and watching how quickly it is carried downstream. However, because the stream flows quickest at the middle of the stream on the stream surface, this simple method might be misleading. Friction along the base of the stream, where water is flowing past rocks and sediment, makes the water move slower in these areas. Therefore, to get an accurate picture of how fast the stream flows, many measurements of velocity at many different points across a stream and at many different depths need to be made in order to get average velocity for the stream.

The cross section and stream velocity are tied closely to one another. In most cases, the same volume of water moving through a stream in one location is about the same volume of water moving through the same stream at a point 100 yards down stream. Yet, the water may be moving faster in one location than the other. Maybe one location has rapids, where the water seems to be full of energy. This is a factor of the cross section. If the stream narrows through a canyon, then that same volume of water has to move much quicker to get through. Likewise, if the stream banks get wider, then the streamflow slows down accordingly. The velocity of the stream is controlled by the surrounding channel conditions.

Scientists calculate streamflow by making a number of measurements of depth and velocity across the stream. This is done using a flowmeter, which consists of a rod that can measure water depth and an attached set of cups that spin in the water as the flow passes by. The spinning cups will click with each

USGS scientist measuring streamflow. Yellow tape is used to determine the location of the streamflow measurement at that cross section.

rotation, so that the scientist can count the number of clicks over a period of time (for example, one minute) and calculate the velocity of the stream at that depth and location along the cross section.

Because it is important to get a good profile of the stream due to the changes in the channel bottom and variations in velocity, scientists make many measurements along each cross section. Typically, the stream is divided into sections so that each section has no more than about 5 percent of the total streamflow. This means that the scientist needs to measure the depth and velocity at about 20 to 25 locations across the stream. Also, because the stream velocity changes with depth, measurements of velocity are made at depths of 60 percent (shallow streams) or 20 percent and 80 percent (deep streams) of the total depth for each section. Calculations have shown that averaging the velocities at these depths gives a good estimate of the average velocity for that particular section.

By calculating the average velocity and depth of water at each measuring point along a stream cross section, a discharge can be calculated for each section. Then, by adding all the discharges together, a total discharge for a stream at a location can be calculated. USGS scientists typically visit a stream about every 6 weeks to make these measurements.

Because streamflow can vary greatly in between visits to a site, information about stream stage (the height of the water in the stream) is collected. This is done by measuring the level directly in the stream, or in many cases, through a stilling well. A stilling well is a large shaft that goes into the ground near a stream and has a pipe from the shaft that is open in the stream. Water levels in the stilling well are the same as the levels in the stream, so changes in stream stage can be measured in the stilling well. A small gage house often is built over the stilling well. In the gage house are instruments that record the changes in the stage. Scientists either collect the recorded information when visiting the site every 6 weeks or it is transmitted via satellite to the science offices and presented on the internet.

If enough measurements of stream discharge and stream stage are made over time, a relation between the two values can be determined. This is very useful because scientists can then use measurements of stream stage to estimate discharge. Therefore, the stream discharge in between the times a site is visited can be determined using the continuous stage measurements.

Obviously, there is much more to making and using streamflow measurements, but this gives a general overview of how and why the measurements are collected.

USGS gage house at Upper Truckee River.
Photograph by Emil Stockton, USGS.

Crest-stage gage at Lamoille Creek.

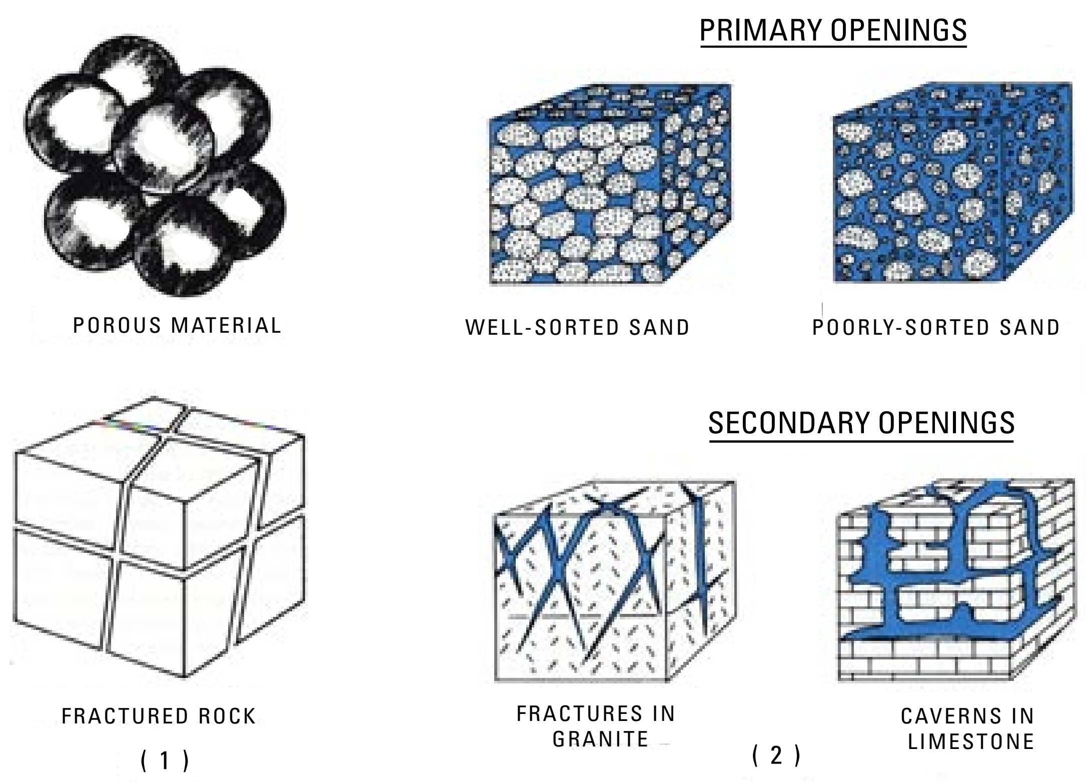
CHAPTER 7

Porosity

The study of water in the environment is called hydrology. Along these lines, a scientist who studies the occurrence and movement of water is called a hydrologist. Although many hydrologists have degrees in geology, there is a difference in the focus of each science. One can think of it in this way: a geologist is interested in the rocks and sediments that make up the Earth, whereas, a hydrologist is interested in the spaces within the rocks and sediments. The reason a hydrologist has this focus is that these spaces can hold water. Porosity is the term for the spaces in rocks and sediments. In simple terms, the more porous a rock or sediment, the more water it can store.

Porosity is the ratio of the volume of pores in a rock unit compared to the overall volume of the rock unit. Porosity is usually presented as a number (or percent), typically between 0 and 0.6 (or 0 and 60 percent).

Why do rocks have pores? Sedimentary rocks, such as sandstone and limestone, are made up of grains of rock that were deposited on the Earth's surface sometime in the past and then became cemented or tightly packed together over time. Some examples of environments that can result in sedimentary rocks are oceans, rivers, alluvial fans along the edges of mountain ranges, sand dunes, and lakes. Because the grains in sediment do not pack together edge-to-edge like a jigsaw puzzle, but rather more like ball bearings in a bucket, plenty of pore spaces exist between the grains.



Source: Heath, 1989.

Many factors control the porosity of sedimentary rocks. Some of these include the roundness of the grains (the more angular the grains, the further apart the grains will pack together, therefore the more porous), sorting (if there are two grain sizes in one deposit, the smaller grains will fill the voids between the larger grains, thereby reducing the porosity), and degree of cementation (some grains get cemented together by minerals such as calcium carbonate or by mud that fills the voids). So, assigning a number for porosity to a sedimentary rock is not a simple matter and each type of rock can have a range of porosity values that depend on these variables.

Igneous and metamorphic rocks typically have very low values of porosity. For igneous rocks, such as granites and basalts, the low porosity is because the rocks were formed from the cooling of molten magma. As the rocks formed, the crystals in the magma interlocked and formed tight bonds. This does not allow for much pore space. One exception would be volcanic rocks, which are full of hot gases when they form. These rocks can have abundant pores due to the gas bubbles present as the lava cools and the rock forms.

Metamorphic rocks are formed under extreme pressure and temperature. When other rocks, such as sandstones or granites, are subjected to great pressures and temperatures, the rocks get altered and form metamorphic rocks. Because metamorphic rocks have been under such pressures and temperatures, any pore spaces that might have been present in the rock get reduced or erased. Examples of metamorphic rocks are schist, marble, and slate.

The type of porosity discussed above is what is referred to as “primary porosity.” Primary porosity is the porosity that results from the original formation of the rocks. However, many rocks undergo changes after formation that can greatly alter (usually increase) their porosity. For example, limestone can dissolve and form caves and caverns. Obviously, the occurrence of large openings such as caves would greatly enhance the porosity.

Many rocks contain joints, faults and/or fractures, which also enhance porosity. For example, most dense granite has a primary porosity of 0 to 5 percent. However, fractures in the granite can produce a secondary porosity of more than twice this amount. In many settings, secondary porosity can be much more important than primary porosity when it comes to storing water in aquifers.

Another aspect of porosity worth mentioning is effective porosity. The effective porosity relates to the connection between pores and fractures, and therefore the ability to transmit water. A rock may have a large porosity, but if the pores are not connected, then the effective porosity may be small.

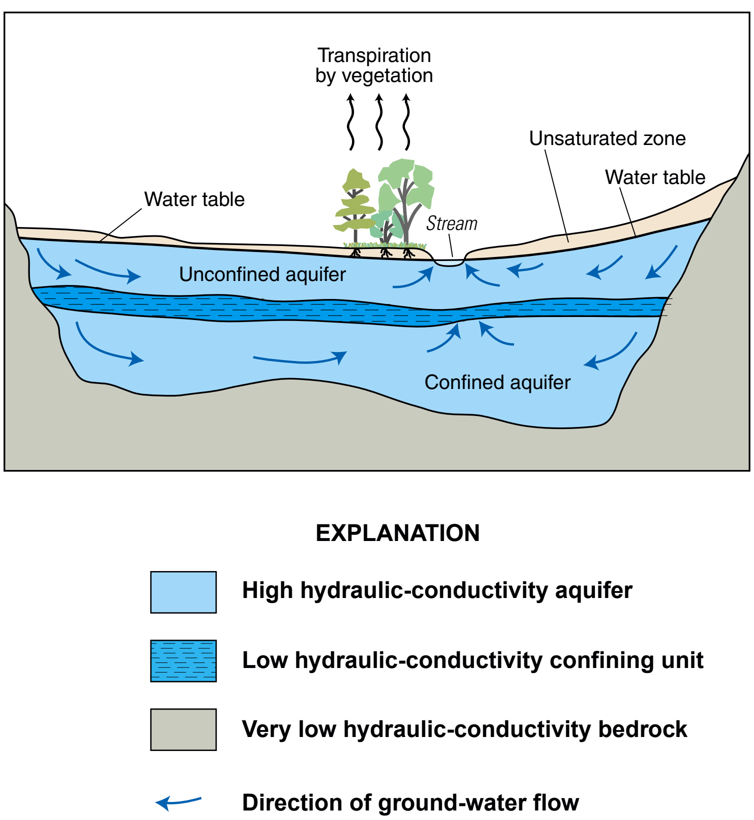
An example is the volcanic rock previously mentioned, where gas bubbles in the rock gave it a large porosity. However, unless the voids are interconnected, water cannot get into and out of the rock. So, the effective porosity would be small. Effective porosity is always a smaller number than true porosity because there is always some degree of isolation of pores in a rock. For hydrology purposes, effective porosity is the value that is used when describing an aquifer.

Chapter 8

Aquifers and Confining Units

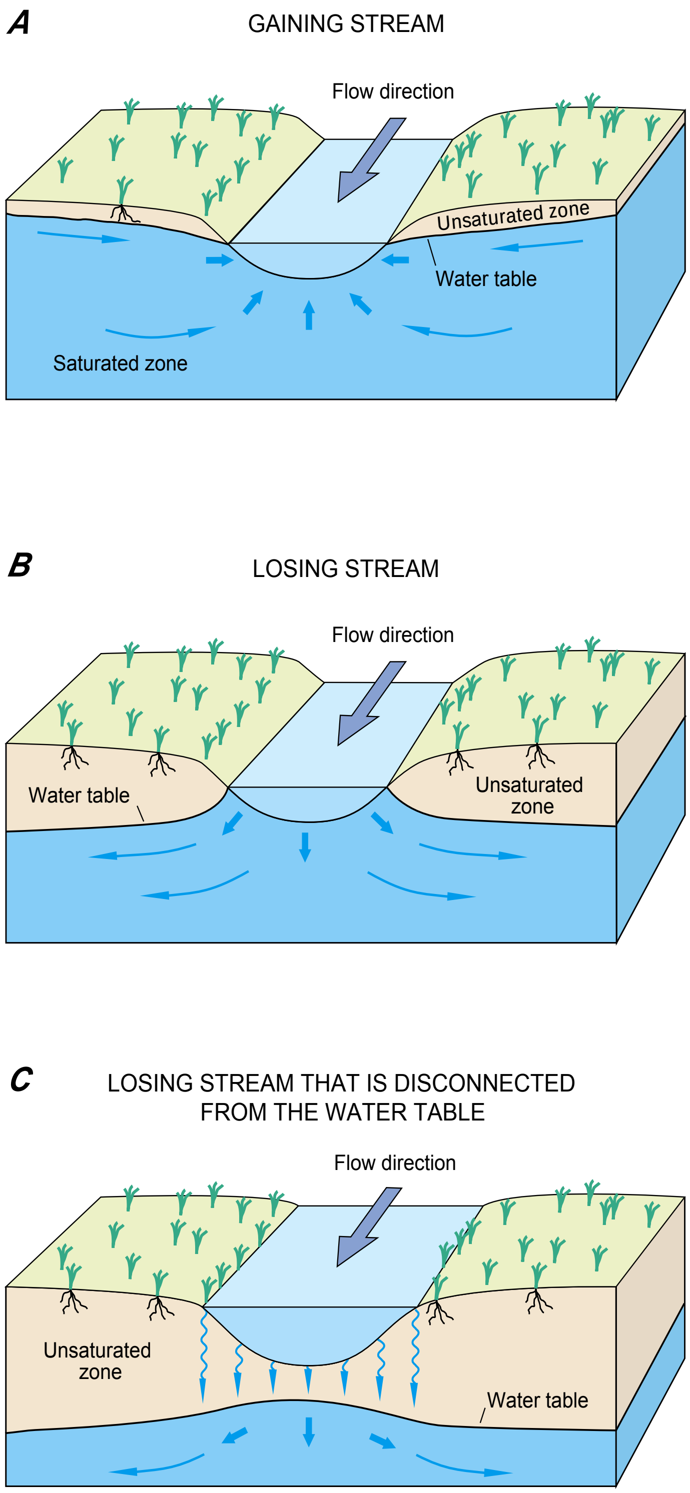
An aquifer is a geologic unit that can store and transmit water in sufficient quantities and rates in order to supply wells. It's a pretty nebulous term and in reality, one person's aquifer is another person's confining unit. For example, in many parts of South Dakota, the Pierre Shale is a source of water for local residents in rural areas because at shallow depths, wells produce a few gallons per minute. However, on a regional scale, the Pierre Shale is widely considered a confining unit; that is, a geologic unit that inhibits flow. In eastern Nevada, there are areas where siltstones are considered confining units to underlying aquifers, yet in some locations, fractures and faults in the siltstones allow large quantities of water to be withdrawn. In the Sierra Nevada, granitic rocks usually are considered to be impermeable, yet where fractured, these can be sources of water for domestic and municipal use. So, the term aquifer often has a local or regional definition depending on specific settings.

For most parts of the country, an aquifer is considered to supply reasonable rates of ground water if one can pump at least 5–10 gallons per minute from a well. This is sufficient for many domestic (household) needs, but not for most communities. Many times this amount of water would need to be pumped to supply the needs for residential, municipal, and industrial requirements for a larger population.



Source: Alley and others, 1999.

Aquifers can be unconfined or confined. An unconfined aquifer is one where the water in the aquifer is open to the air. These also are referred to as water table aquifers. In such conditions, water that falls on the land surface as rainfall or snow can infiltrate into the ground to the depth where the pore spaces are completely saturated. Therefore, if a person put a well into an unconfined aquifer, the water in the well would reflect the depth of the water table (the surface below which there is 100 percent saturation of all the pores in the aquifer).

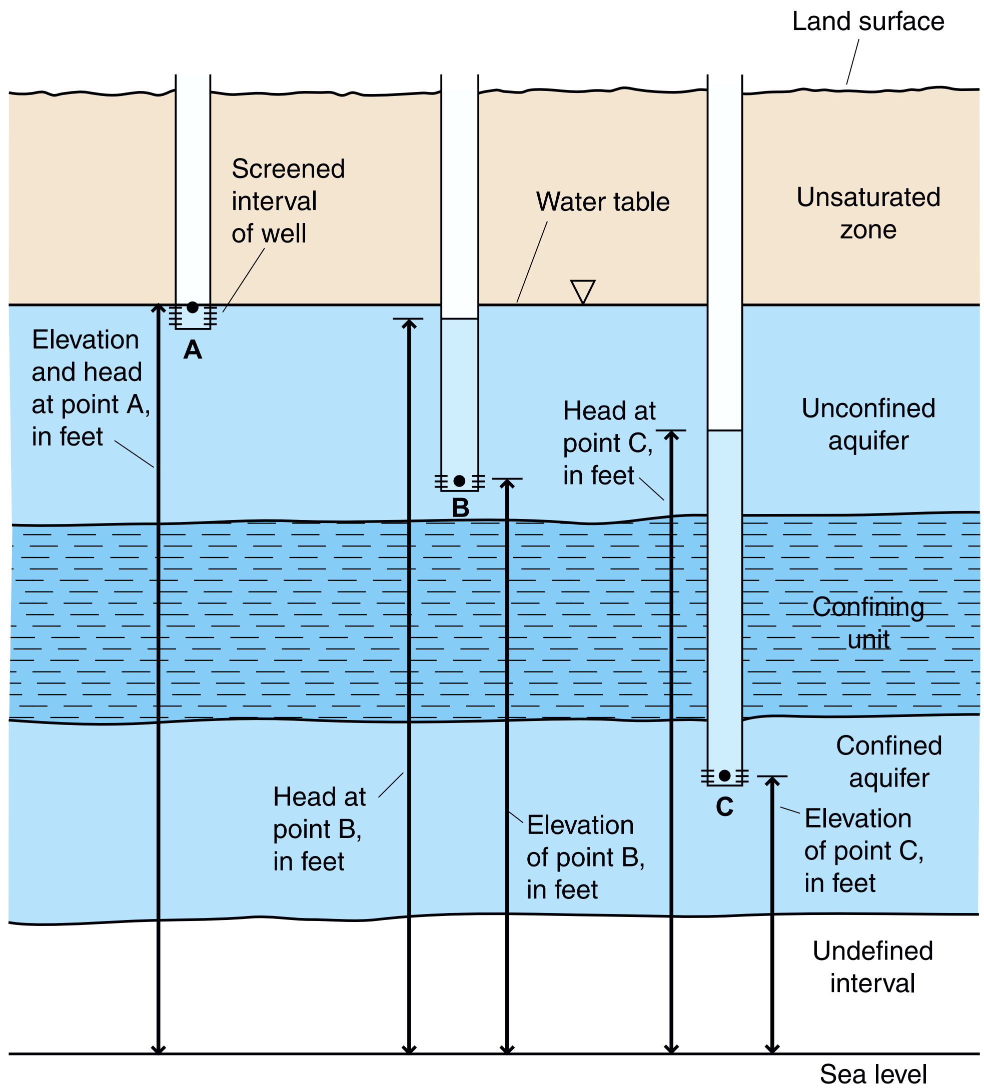


Source: Alley and others, 1999.

Sometimes streams leak into the ground and actually recharge (supply) these aquifers. These are called losing streams. A good example of this would be along the edge of mountain ranges where streams coming off of ridges disappear before reaching the valley floor. In other cases, streams gain flow along their course and these are gaining streams. In other words, ground water is contributing to streamflow. A good example of this would be an area of springs that can occur in the central part of some valleys. Many lakes and wetlands are areas where the water table intersects the land surface. In these situations, the lakes and wetlands are “windows” to the water table.

The other type of aquifer is a confined aquifer. This is where the geologic unit that stores water is isolated from the air by some unit that restricts water movement, typically a shale or clay unit. These aquifers also are referred to as artesian. If a person puts a well in a confined aquifer, the water in the well will rise to a level somewhere above the top of the aquifer because the aquifer is sealed by the overlying strata (the confining unit). If the pressure is great enough, the water level in the well could rise above the land surface and flow. Confined aquifers are saturated entirely, unlike unconfined aquifers where air-filled pore spaces exist above the water table.

Aquifers in the Basin and Range of much of Eastern Nevada are comprised primarily of three major hydrogeologic units: (1) the alluvial aquifer, which is the material that makes up the valleys between mountain ranges. Alluvial aquifers mostly consist of gravels, sands, silts, and clays, and typically are unconfined. However, because of clay and silt layers within the alluvium, some parts of the alluvial aquifer may act confined, (2) the carbonate aquifer, which is mainly made up of limestone and dolomite. These rocks comprise many mountain ranges and underlie the alluvial aquifer in places. This aquifer can be either unconfined or confined, depending on the setting,



Source: Alley and others, 1999.

and (3) the volcanic rocks aquifer, like the carbonate aquifer, makes up many mountain ridges and can underlie the alluvial aquifer. Likewise, this aquifer can be either unconfined or confined depending on the local setting.

In summary, water stored underground in geologic units in sufficient quantities for use occurs in either unconfined or confined aquifers. Both aquifers are important sources for water and many places rely entirely on the water stored in the ground for their water supplies.

Lost Man Hot Springs. Photograph by Daron Tanko, USGS.

Chapter 9

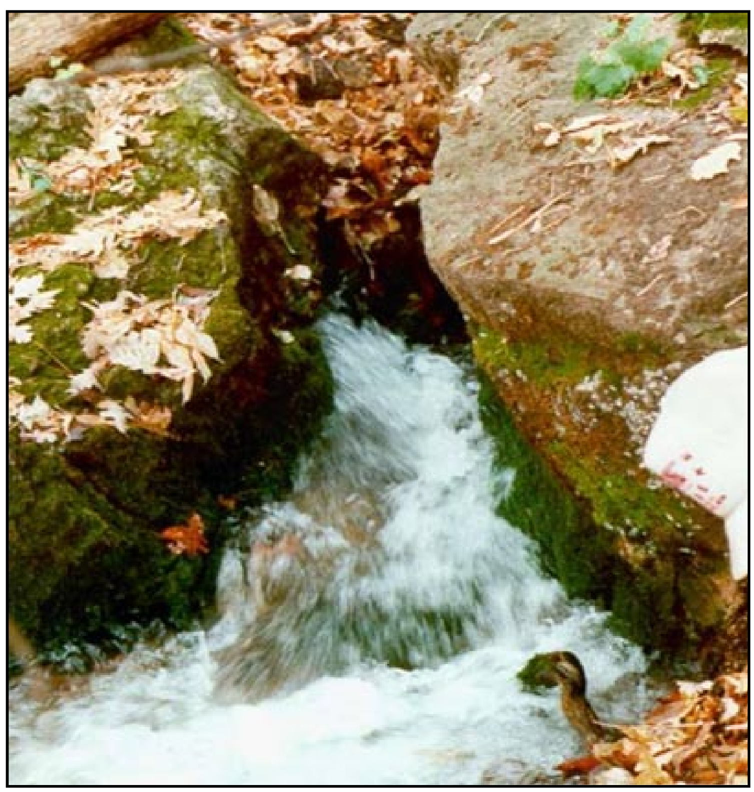
Springs

Springs are the locations where water discharges out of the ground onto the land surface. As mentioned earlier, springs are a unique setting in that they are a transition between ground water and surface water. Because of this, when hydrologists studying an area are categorizing water into either ground water or surface water, springs can represent both. Obviously, once the water is out of the ground and on the land surface, it becomes surface water. But, because the water is being discharged from the ground, hydrologists can sample it for water quality, age dates, and other factors measured in ground water. Plus, if one is measuring the depth to ground water in an area, springs represent the zero depth. Therefore, springs can be labeled as ground water and surface water.

Scientists are good at taking a topic and breaking it into many numerous categories and definitions based on small variations. Springs are no exception and many different types of springs can be discussed. However, for most of Nevada, springs can broken into five groups: fracture springs, bedding springs, alluvial-fan springs, water-table springs, and basin springs. Various scientific terms are used for different types of springs and many subcategories for each, but for this general discussion, these five labels will work just fine.

Just as a side note, springs can usually be identified on maps and aerial photographs by the concentration of trees and plants in specific locations. Springs provide the water to support abundant plant life in areas where little else grows. So, maps and aerial photographs are useful tools for finding springs.

In the canyons of the mountains throughout Nevada, springs often occur right out of the bedrock. These are fracture springs. Rainfall and snowmelt in the mountains seeps into cracks and fractures in the bedrock and travels underground through these openings until it reaches a low area such as a canyon. At this point, the water seeps out of the fractures and onto the surface. In most settings, the water in fracture springs is pretty recent in age, meaning that the water that seeps into the cracks and fractures as precipitation and snowmelt moves relatively quickly to the springs.



Spring discharging from fractured bedrock (hat for scale). Photograph by M.L. Strobel, USGS.

Bedding springs also are noticeable in the mountain and canyon areas. When one type of rock is setting on top of a different type of rock, it is called bedding. A good example of bedding is the Grand Canyon, where one can see many different layers of rocks stacked on top of each other like a stack of pancakes. Some rocks can transmit water easier than others (refer to previous chapters that discussed aquifers and confining units). When a rock type that transmits water easily sits above a rock type that is mostly impermeable, the water in the upper rocks tends to move laterally instead of downward. So, when there is a canyon where both rock types are exposed, the water in the upper rocks will seep out right at their base where they overlie the impermeable rocks. Quite often, bedding springs are the locations of vegetation such as trees and bushes that occur on the walls of canyons.

An alluvial fan is the area of rocks and sand at the mouth of a canyon coming off of the mountains. As water moves down a canyon, it carries sediment with it. The sediment can get deposited out onto the valley floor as the stream leaves the canyon. Over many years, the sediments build up and form a fan-shaped feature near the mouth of a canyon (similar in principle to a river delta) which is called an alluvial fan. In some cases, streams leaving the mountain canyons can disappear into the ground near the tops of alluvial fans because the fans are so porous. However, this water will seep back out near the base of the fans. These are alluvial-fan springs. Often, homes and clusters of trees are situated at the base of alluvial fans in Nevada where these springs occur.

Water-table springs occur near the middle of valleys in the Basin and Range of Nevada. This is where the ground water is high enough to intersect land surface and the water exits the ground. Typically these areas are locations of wetlands or lakes. Some people would not call these springs because the water does not actually “spring” out onto the surface as it does in the previous examples. But nevertheless, it is ground water discharging onto the surface and therefore can be considered a spring.

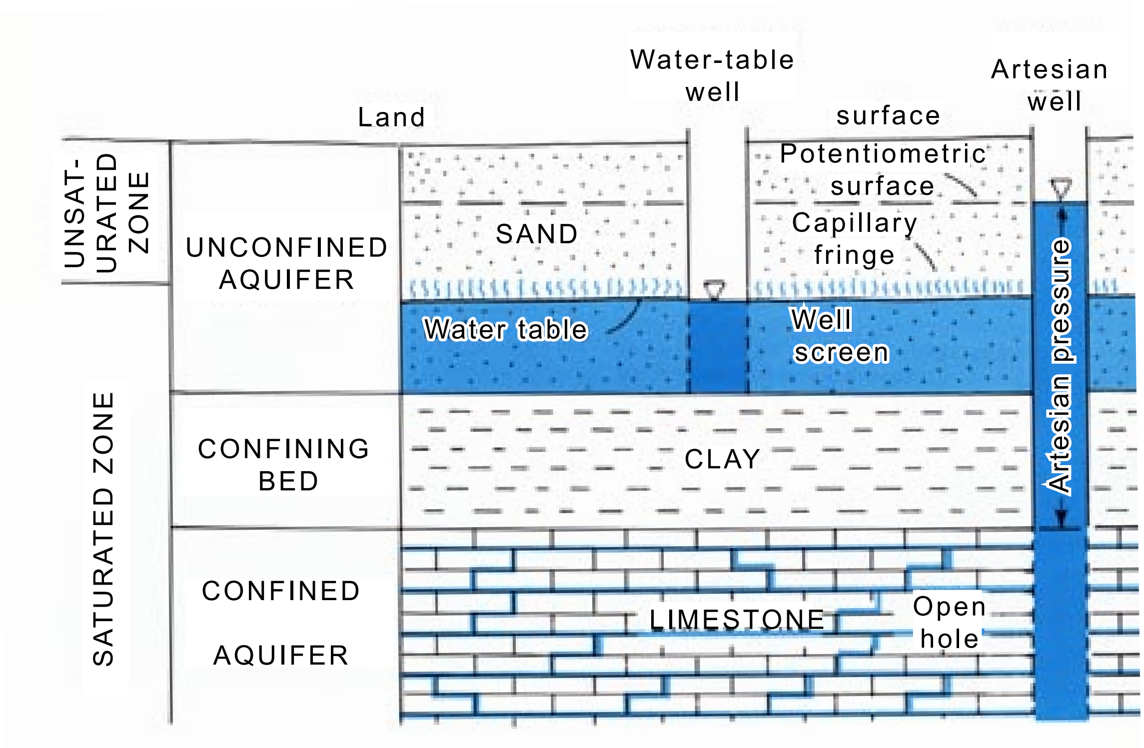
The last type is what we are calling basin springs. Ground water tends to move downgradient within a basin and tries to discharge into the next basin. Often, as the ground water encounters less permeable rocks at the low end of the basin, it gets backed up and seeps out onto the surface. This seepage at the end of a basin is a basin spring. The huge ground-water flow system in eastern Nevada is a series of basins that extend from White Pine County southward to near the Colorado River. At the end of this flow system are a number of basin springs (such as Muddy Springs) where the ground water moving downgradient in the basins gets discharged to the surface. The amount of water being discharged at these springs is not a huge quantity, but it is a pretty steady rate of discharge and represents a very large flow system.

Springs are very useful to hydrologists for looking at changes in natural conditions. In all five examples, changes in the amount of water being discharged at springs would indicate changes in the water balance of an area. Reduced recharge from precipitation and snowmelt, such as what occurs during a drought, can decrease the amount and duration of flow from springs. Changes in ET due to changes in the type and amount of vegetation cover can alter ground-water levels and affect spring discharge. Human impacts from pumping certainly can have an affect on the ground-water levels and availability of water to feed the springs. Scientists can use data from springs to make conclusions about how various factors, both natural and human, are affecting the water resources in an area.

Chapter 10

Unsaturated Zone

The water table is the top of an unconfined aquifer where the water pressure is equal to atmospheric pressure. The water level in a well in an unconfined aquifer represents the water table. There is a small zone above the water table that also is 100 percent saturated. This is called the capillary fringe and the reason this is saturated is that the surface tension of water and attractive forces of the sediments wick water up from the water table and hold it in the pore spaces (sort of like the "paper towel" effect, where if a corner of a paper towel is placed into a puddle of liquid, the liquid would be pulled up into the towel by capillary tension).



Source: Heath, 1989

The area above the capillary fringe and land surface also holds water, but less than 100 percent saturation. In other words, the pore spaces are filled with both water and air. Scientists refer to the area between the water table and land surface as the unsaturated zone, zone of aeration, or vadose zone (all three terms refer to the same area). The term most people are most familiar with would be soil moisture, which refers to the water in the unsaturated zone that lies within the depth of plant roots.

The same tension that pulls water up from the water table into the capillary fringe also holds water in the unsaturated zone. The amount of water in the unsaturated zone is related to the porosity of the sediments, the thickness of the unsaturated zone, and how recent infiltration (whether from precipitation or irrigation) has occurred. Other factors, such as climate conditions and vegetation cover, also are important, but this chapter will discuss only the first three.

Porosity is the ratio of the spaces or openings in a rock or sediment compared to the total volume of the rock or sediment. Porosity is important because the smaller the pore spaces, the higher the tension between the water and the rocks or sediments. For example, in a gravel bed, the amount of water content in the unsaturated zone would be smaller than in a silt bed because the pore spaces between the gravel would be much larger in size than those in the silt. This is why the capillary fringe is quite large in clay or silt deposits verses what is observed in sand or gravel deposits. This also is why clayey soils are often referred to as poorly drained and sandy soils are often referred to as well drained.

The thickness of the unsaturated zone is important because sediments near the water table but in the unsaturated zone have a source of moisture (especially as the water table fluctuates up and down with recharge and discharge). The capillary fringe is where the sediments are completely saturated. Above the capillary fringe, water content in sediments can still be very high. The amount of water content typically will decrease with distance above the capillary fringe.

The thickness also is important because thin unsaturated zones can be entirely within the reach of plant roots (in the soil moisture zone) and affected by plant uptake. Also, depending on the climate and plant cover, water content near the land surface can evaporate and move as vapor upward through the pore spaces.

Water content in the unsaturated zone fluctuates depending on how recent infiltration has occurred. Following a rain or irrigation, the upper part of the unsaturated zone will have a high water content. Some of this water will then move downward by the force of gravity and will reach the water table. Some of the water will be lost to ET (lost to evaporation or taken up by plants). And some of the water will be held in pore spaces in the unsaturated zone. Over time, gravity will continue to pull some of the water downward and some moisture will convert to vapor and move upward. This is why water content in the unsaturated zone varies over time.

Water content can be measured in various ways in the unsaturated zone. One method involves removing a block of sediment, taking it to the laboratory, and measuring how much moisture is lost when the sample is baked. In the field, electric currents, passed through a portion of the unsaturated zone using a series of probes, can be measured to determine the water content. Neutron probes, which measure the velocity of neutrons when applied to different sediments, are used to measure changes in water content with depth and time at specific locations.

An instrument often used to examine water content in the unsaturated zone is called a tensiometer. At the beginning of this chapter, water table was defined as where the water pressure equals atmospheric pressure. This means that below the water table, water pressure is above atmospheric pressure, and above the water table, water pressure is below atmospheric pressure (we refer to this as a negative water pressure). The amount of water content is measured by measuring the water pressure.

A tensiometer consists of a sealed tube with a porous membrane over the bottom end. Tensiometers are placed at various depths in the unsaturated zone in order to measure the differences in water content with depth (the gradient in the unsaturated zone). Because the water pressure is negative in the unsaturated zone, vacuum pressure is applied to the inside of the tensiometer such that moisture will move from the sediments through the porous membrane into the tensiometer. The amount of vacuum applied and the amount of water movement into the tensiometer can be used to determine the water content at specific depths.

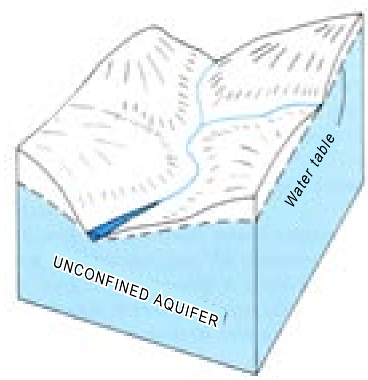
The unsaturated zone is important because it affects how much water recharges aquifers, relates to the health of crops and other vegetation, provides the environment that many plants and animals depend upon, and can be an important area in contaminant transport and containment. The unsaturated zone needs to be understood in order to better understand water resources and water budgets.

CHAPTER 11

Ground-Water Flow

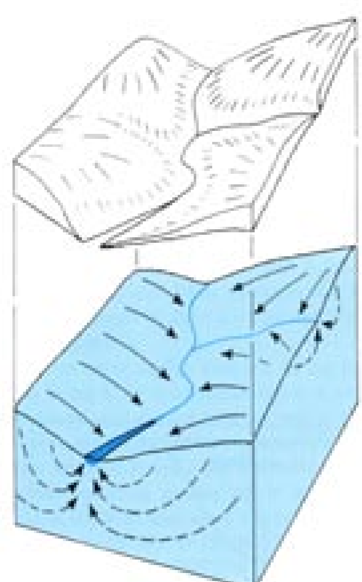
Ground-water occurrence and movement are concepts many people may not understand. For centuries, ground water has been a mystery because it was under the ground and out of sight. Many people use to think of it as magical because of the way water disappeared into the ground (infiltration) and appeared again on the land surface (springs). People created stories of great underground rivers and lakes and other colorful concepts for ground water. People often use stories to explain what they do not understand, but ground-water flow really is a simple concept.

In most cases, ground water occurs in the pore spaces in rocks and sediments. Some water gets into the pores as recharge, where the water on the land surface (rainfall, snowmelt, rivers, etc.) seeps into the ground and moves to the water table. In some cases, especially in really deep aquifers, the water can be what we call connate, which means the water has been there since the rocks or sediments were deposited. Most sedimentary rocks are formed in water environments, whether its sediments deposited at the bottom of an ocean, river sediments, lake sediments, or even alluvial fans. As these sediments are deposited, water gets trapped in the pore spaces and can stay there for very long periods of time. However, most water in aquifers that people use tends to be close to land surface and relatively recent recharge.



Once in the ground, water moves from pore space to pore space. The movement can be really slow in rocks and sediments that are fine grained, such as in clays and silts. The movement can be pretty fast in gravels and other coarse materials. How water moves through sediments can be observed by filling a glass jar with sand and then pouring water into the jar. The water will move between the grains and slowly move downward because of gravity. This movement from pore space to pore space is how ground water flows.

In cases where there are cracks and fractures in the rocks, water can move through these much quicker than it can through the solid rock. The cracks and fractures can be thought of as huge pores that water can fill and move through with little resistance. These are sort of like ground-water superhighways. Many drillers putting wells in bedrock areas hope to encounter cracks and fractures because these can greatly increase the rate of water flow going to the well. In some areas in the country, drillers actually use high pressure (called hydro-fracturing) to rupture the rocks deep in the ground in order to increase ground-water flow to wells. Cracks and fractures can greatly enhance the rate of ground-water flow as compared to the movement between pore spaces alone.



Arrows show direction of ground-water movement

Source: Heath, 1989.

Ground water in unconfined aquifers moves due to gravity. So, ground water tends to move from higher elevations to lower elevations. This is how water that enters the ground in the mountains ends up in the basins of Nevada. It also is how water moves across a basin and from one basin to another. Gravity is the driving force in such cases. Scientists will measure water levels in a number of wells in a basin in order to get a good understanding of the directions of ground-water movement across the basin.

In deep confined aquifers, gravity is not as important as pressure. Going back to the chapter where confined and unconfined aquifers were discussed, confined aquifers were defined as geologic units filled with water and are confined both above and below by confining units (such as shale or clays). Think of a confined aquifer like a large bladder or water bed, where the water is held by the surrounding less-permeable units. On a bladder or water bed, if one corner is pressed, the water would tend to move towards the other side and bulge up. This is similar to a confined aquifer. Ground water in a confined aquifer moves because of pressure and will flow from a point of higher pressure to lower pressure. Ground-water flow in a confined aquifer may be in a different direction than the ground-water flow in the overlying unconfined aquifer simply because they are driven by different forces (gravity versus pressure).

It was mentioned in the beginning of this chapter that people created stories about underground rivers and lakes. In the vast majority of settings, ground water occurs only in pore spaces and in small cracks and fractures. However, in special settings when there is limestone and dolomite as the bedrock, caverns can occur. Because many people have been into caves and seen ground water in some of the caverns, stories of huge underground rivers and lakes have been used to describe ground-water occurrence and flow. Keep in mind that this is the exception and not the rule for most places. Some people talk about a huge underground lake that extends from South Dakota and Nebraska all the way to Texas and New Mexico. In reality, this is the High Plains aquifer and it's a large sand unit that extends along the front range of the Rocky Mountains. It is a huge, continuous aquifer and the water occurs in the pore spaces between the sand grains. It is well studied and understood, but people still tend to use stories about this great underground lake.

Chapter 12

Hydraulic Conductivity

Hydraulic conductivity is a term that is used when describing hydrogeologic units. It is a way to quantify or describe the permeability of a rock or sediment. Breaking the term down, the first part, hydraulic, refers to fluid. Most people are familiar with the basic concepts of hydraulic tools or hydraulic brakes. These are mechanisms that use the movement of a fluid to produce some action. In the case of hydraulic conductivity, this refers to the movement of water. The second part, conductivity, refers to the ease of some action to occur. The opposite of conductivity is resistivity.

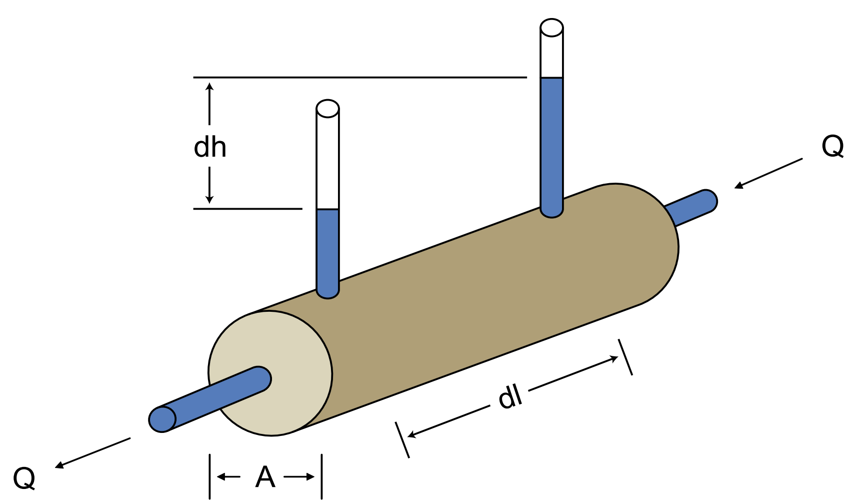
Thinking in terms of electricity, the more conductive something may be, the easier it is for electric current to pass through it (metal is very conductive, whereas wood and plastic are not). In terms of water, conductance is the ability for a fluid to move through a medium, such as a rock or sediment. Therefore, hydraulic conductivity is the measure of how water passes through a geologic material.

Now for some history. The term was introduced by a French engineer named Henry Darcy back in 1856. Darcy was looking at different geologic materials and trying to determine which ones would be best suited for filtering the water used by the city of Dijon. He thought there should be a way to quantify the different permeabilities of these sands and gravels. He took a bunch of samples of sediments he collected in the areas around Dijon and brought them back to his lab. He set up an experiment where he put the sediments in long tubes and ran water through each of them. Then, he measured the time it took for the water to move through each sample and he found that he could get similar results for the same sediment each time he did the experiment. The result was that Henry Darcy assigned numbers to the sediments that quantified how conductive each was to water movement.

The overlying principle for ground-water flow is what is now referred to as Darcy's Law. Darcy's Law is the equation:

$$Q = -K\,A\,dh/dl$$

Where Q is the discharge, K is the hydraulic conductivity, A is the cross-sectional area of the flow, and dh/dl is the hydraulic gradient. This equation can be visualized by looking at the illustration below:



In this illustration, Q shows the water going into and out of the tube, A is the cross-sectional area of flow (equals πr^2), dh is the difference between water levels (head) in the two observation tubes (analogous to wells), and dl is the distance between the two observation tubes. The large tube is filled with aquifer material, such as sand or gravel. By measuring the parameters shown, the hydraulic conductivity can be calculated.

Hydraulic conductivity is expressed as a measure of length versus time. For example, hydraulic conductivity might be shown as a number in feet per day. Or the number could be meters per second. Many different units of numbers can be used, but all relate to the same value of hydraulic conductivity. In a general sense, the number can be used to visualize how quickly water can move through a material.

Two other factors can affect hydraulic conductivity: viscosity and density. Viscosity is a term for the ease of a fluid to flow. For example, pancake syrup is pretty viscous compared to water. If a bottle of pancake syrup is heated, it certainly will flow much easier than it will when it is cold. This shows that the viscosity is related to temperature. In ground water, the temperature of the water can make a difference on how quickly it moves through the rocks and sediments. Therefore, the hydraulic conductivity can be altered by the temperature (changing the viscosity of the water).

Density is a measure of the weight of something per volume. With water, the more dissolved constituents in the water, the higher the density. As one can imagine, seawater is much denser than freshwater. As density increases, the ease of movement of water through the rock or sediment decreases. Therefore, density also can alter the hydraulic conductivity of a material.

When thinking about hydraulic conductivity as a measure of permeability, it can generally be concluded that rocks and sediments with large pore spaces will have larger hydraulic conductivities than those with very small pores. For example, in looking at sediments, clay (very small particles packed close together) has a range of hydraulic conductivities of about 0.000001 to 0.001 feet per day. Sand, on the other hand, has a much larger range of hydraulic conductivities, usually about 1 to 100 feet per day. Gravel can be quite large, at about 10 to 1,000 feet per day. Hydraulic conductivities can have a wide range for each type of rock or sediment, and the larger the pore openings, the greater the value of hydraulic conductivity.

Chapter 13

Well Construction

Ground water has been discussed in earlier chapters, but how to access ground water for measuring water levels, sampling water quality, and doing aquifer tests has not been described. Springs are one way to get in touch with ground water, because these are locations of ground-water discharge to the surface. But in areas where springs do not occur, hydrologists will install wells to access ground water.

In general, wells are a deep subject, so-to-speak, and this chapter won't get into all the details of how to drill and install all types of wells because this really depends on the local geology, hydrologic characteristics, depth to water, and various local, State, and Federal regulations. In this chapter, the general methods for constructing a well will be discussed.

Typically, wells are used for either water supply or scientific observation and sampling. The diameter of water-supply wells depends on the how much water is needed for specific uses. For domestic (single home) wells, the optimum diameter for well casings is around 6 inches, in which a submersible pump typically can produce up to 50 gallons per minute. For municipal (city) wells, the well diameter would be much larger, typically in the 8 to 30 inches range. Irrigation wells, where water is pumped for crops, also would be in this larger range. In contrast, many wells used for scientific observation of water levels and ground-water sampling are much smaller in diameter, often 2 to 4 inches. Even smaller wells called piezometers can be 1 inch in diameter or smaller.

Therefore, depending on the intended use, wells can widely vary in diameter. In many situations in the past, wells were actually dug by hand instead of using a drill. These wells can be very wide in diameter and often lined with stones, bricks or cement. In such cases, various objects, and even people, were sometimes

known to fall into these wells. Ancient hand-dug wells are valuable archeological sites for recovering a wide array of artifacts and remains. Hand-dug wells are rare in the U.S. today; however, several were constructed in various valleys in Nevada by early settlers and by the Civilian Conservation Corps during the Depression.

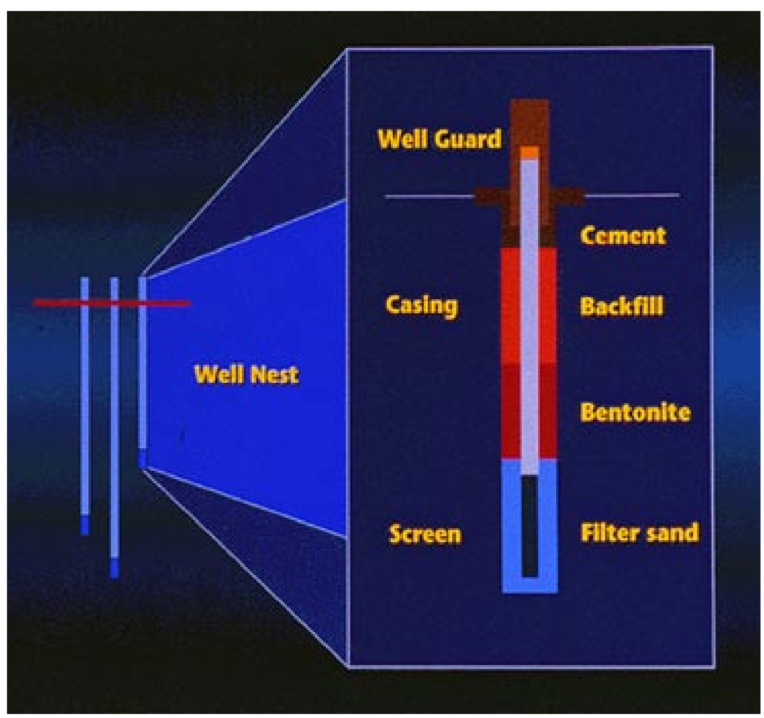
In addition to water supply and scientific observation, there are special cases for well installation. In areas of mining, wells are installed and pumped in order to lower the water table (and keep the deep mines dry). These are referred to as dewatering wells. Some wells are used for injection of water or contaminants into the ground. Many larger municipal areas now use injection wells to artificially recharge aquifers and store water underground.

Once a site has been determined for well installation (based on the hydrogeology and intended use), a well driller will be contracted to drill a hole and install a well. The type of drill used depends on the geology and depth to water from land surface. If more than one well is installed at a site, often where each well is open to different depths, the group of wells is referred to as a well nest.

In areas of unconsolidated (loose) sediments, such as in the basins of Nevada, and where the water table is less than a few hundred feet below the surface, an auger may be used, mainly for monitoring wells. This is a drill with a hollow stem in the center surrounded by auger flights to carry the cut sediments to the surface during augering. It looks a lot like a giant wood drill. The reason for the hollow stem is that the driller will auger down to beneath the water table, then place the well casing (the pipe that serves as the well) down the center of the stem and into the aquifer. The auger is left in place during this process to keep the surrounding sediments from caving in while the well is being installed. Once the well is in place, the auger is pulled up and the well is one step closer to being finished.

For domestic, municipal, or irrigation wells, or in situations where there is either solid rock or many large boulders or where one needs to drill really deep to reach water, then different drills are used. This chapter won't go into detail on these different drills, but they include cable-tool drills and direct-rotary drills, among many other types. The main objective of any of these drills is to put a hole in the ground to the aquifer and install a well. In deeper drilling methods, drillers often will inject a thick drilling mud to keep the hole open from collapse while the well is being installed.

Once the hole is in the ground, the well can be installed. In unconsolidated sediments and weathered bedrock, a well may require a well screen. A well screen is a section of slots or openings in the well casing that allows water to come into the well but holds out the sediments. Around a well screen, a driller will place filter sand, which is sand that is used to separate the surrounding sediments from the well screen and allows water to flow to the screen. The length of the screened interval of the well depends on the purpose of the well. If one wants to pump for water supply, then the screen typically will be long (10 to 20 feet or longer). If one wants to sample a specific location in an aquifer for scientific study, then a screen might only be a few feet to a few inches in length.



In consolidated bedrock, wells often will not use screens, but rather will be open hole in which water flows from the bedrock into the drilled hole. Areas in the open hole that can transmit large quantities of water, such as fractures, bedding planes, and dissolution features (caverns and holes), can control the productivity of the bedrock well.

Above the screen or open hole in bedrock, the well consists of casing that either is threaded or welded together. The casing can be made of a wide variety of materials, but often is either steel, iron, or PVC plastic. The casing is the well pipe which extends from the aquifer to land surface. Typically, a well pump is lowered down the casing to below the water level. The size and type of pump depends on the depth to water, well diameter, and intended use (how many gallons per minute is needed).

Once the well casing is in place, the well will be finished by placing bentonite (clay) in the space between the drilled hole and the casing (referred to as the well annulus) above the screen or open hole. This bentonite acts as a seal to keep water (and potentially contaminants) from seeping down the annulus and into the well. Above the bentonite seal, natural material from the drilling sometimes is used to fill in the hole. Near land surface, a cement pad is built around the top of the well again to seal the annulus and to protect the well. A heavy metal pipe, referred to as a well guard, often is placed around the top of the well and into the cement pad for added protection of the well casing.

Once well construction is complete, the well must be developed to remove drilling mud and other fine sediment produced during drilling so that the well produces clear water. This is often done by injecting compressed air above the well screen. The compressed air lifts water from the well casing, removing sediment with it and clearing the screen. The process usually takes several hours. Development also can be completed by inserting an old pump into the well and pumping the water from the well at a high rate of discharge to remove sediment. The well is then ready for pump installation for normal use. Many different types of pumps may be used and the subject is worthy of an entire chapter.

This chapter is a simplified overview of how wells are installed and constructed. Other types of wells, drills, and construction designs exist, but this provides a general overview of how many wells are installed. Special considerations and methods need to be used for wells that are very deep (thousands of feet). Innovative well installation methods are now being used that have been successful in producing larger quantities of water than the more traditional methods. Some of these new methods include angular and horizontal drilling in order to follow bedding planes, and hydrofracturing (using high pressures to produce fractures in the bedrock in order to allow more water to flow to the well).

Developing a well after completion. Photograph by D.K. Maurer, USGS.

Well drilling at Summit Lake. Photograph by J.L. Wood, USGS.

Chapter 14

Making a Well Measurement

Note: This chapter is from an article I wrote for the Ely Times following the creation of a citizen's ground-water observation network. Many of the local citizens wanted to participate in data collection, so we worked with them to start a well-monitoring program. The information addresses their specific needs, but certainly is transferable to other parts of Nevada with similar interests.

Because many people have shown an interest in being involved with making ground-water measurements, it may be useful to discuss the basics of the process. For the data to be accurate and applicable for a large monitoring network, it needs to be collected properly. The following are some of the key points:

Well selection: This is an important first step in putting together a monitoring network. Wells need to have good distribution so that a large area has adequate coverage and the wells are not all clustered into groups. Also important is that the various aquifers are represented.

For example, if in a certain valley 200 wells are available for measurement, wells should be selected so that measurements would be made throughout the valley (along the edges and near the center) as well as in the shallow alluvial aquifer and the deep bedrock aquifer. If 10 wells were within a single square mile and all in the alluvial aquifer, all 10 would not need to be measured because the information would be redundant. In this case, just one or two of the wells would need to be measured.

Besides location and aquifer type, important in well selection is the effect of other impacts. For example, one probably would not want to measure a well that is close to an irrigation well during the growing season. The drawdown caused by the irrigation well would affect the water levels in the observation well. This information could be useful for looking at impacts from pumping, but for a large-scale monitoring network, one typically is more interested in natural conditions, not pumping impacts.

Hydrologists can assist in the well selection process. It is important to consider which wells are being monitored by various agencies, so that any new monitoring network contributes to and compliments those efforts. It is important to make sure that wells supply useful information and can be monitored for long periods of time (available for the next few years). Many wells have been monitored in the past as part of other studies, and to select these wells and continue the monitoring would be useful information and would provide a longer period of record.

Well construction: It is really important to have information on the well construction. This is in the form of a drillers' log that is recorded at the time of well installation. The driller records such information as the depth of the well, the length of the casing, the aquifer or geologic material in which the well is open, the length of the well screen or open interval, the type of well casing (steel pipe, PVC, etc.), pumping rate maintained following well installation, and other important information. Many land owners have the logs for their wells, but if not, these are filed with the State of Nevada and can be requested.

Well location: On the well log, the location of the well is provided (typically as either a location based on township, range, and section or in latitude and longitude). More recently, well locations are determined using GPS. Having an accurate well location is very important for the monitoring network.

Making well measurements: Once wells have been selected, doing the actual measurement is relatively simple, but needs to follow a standard procedure. Before going into the field, it is important to make sure one has tools (wrench, pliers, etc.); they may be needed to access some wells. Some observation wells are locked, so obtain keys ahead of time. Also, bring a well measuring tape, chalk, retractable tape measure (such as a carpenter's tape), and a log book to record measurements.

Water levels in wells are measured from the same spot each time. We call this the measuring point, and often it is marked with chalk on the top of the well casing. If there is not an established measuring point, then make the measurement from the north side of the well casing, mark this point with chalk, and record the location in your field notes.

In addition to recording the measuring point, it also is important to record the height of the measuring point above land surface. This is done by using the retractable tape measure and measuring from the measuring point to land at the base of the well.

Pat Glancy and Dave Berger, USGS, making a well measurement.

Electric tape measurements: An electric tape is on a reel and is marked in tenths of feet. The tapes typically are either 100, 500, or 1,000 feet in length. At the end of the tape is a metal probe which sounds a buzzer and a light turns on when it reaches the water in the well. Once this happens, hold the tape to the measuring point and record the depth.

Steel tape measurements: A steel tape is on a reel and is similar to electric tapes in that increments are marked on the tape. The difference is that this measurement requires a little math. First, mark the first 10 feet or so of the tape with chalk so that it is possible to see the water mark easily. Lower the end of the tape into the well and continue until the tape goes into the water. Record the depth at the measuring point, then wind the tape back up out of the well. A water mark will be on the tape, hopefully in the section previously chalked, that will show the depth to water. Record this number. Then, in the log book, subtract the water mark from the measuring point to get true depth to the top of the water level.

For example, the tape is lowered and held at the measuring point at 50.0 feet. The water mark on the tape is at 3.4 feet. This indicates that the depth to water is 46.6 feet below the measuring point. If the measuring point is 2 feet above land surface, then the water in this well is 44.6 feet below land surface.

That is pretty much all there is to making a measurement. Please remember to record where the well is located, the date and time of measurement, and any other observations, such as if there is an irrigation well pumping nearby or if the well is near standing water, etc. These notes prove to be very useful later when evaluating water levels over time.

Once leaving a site, make sure the well is secured (capped and locked), that all tools and equipment are collected, and that all gates and other access are closed. Property owners are much more cooperative when respect is shown for their well and land.

Well measurement at abandoned windmill well in Whiskey Flat, south of Hawthorne, Nevada. Photograph by K.K. Allander, USGS.

Measuring water levels in a monitoring well using an electric tape.

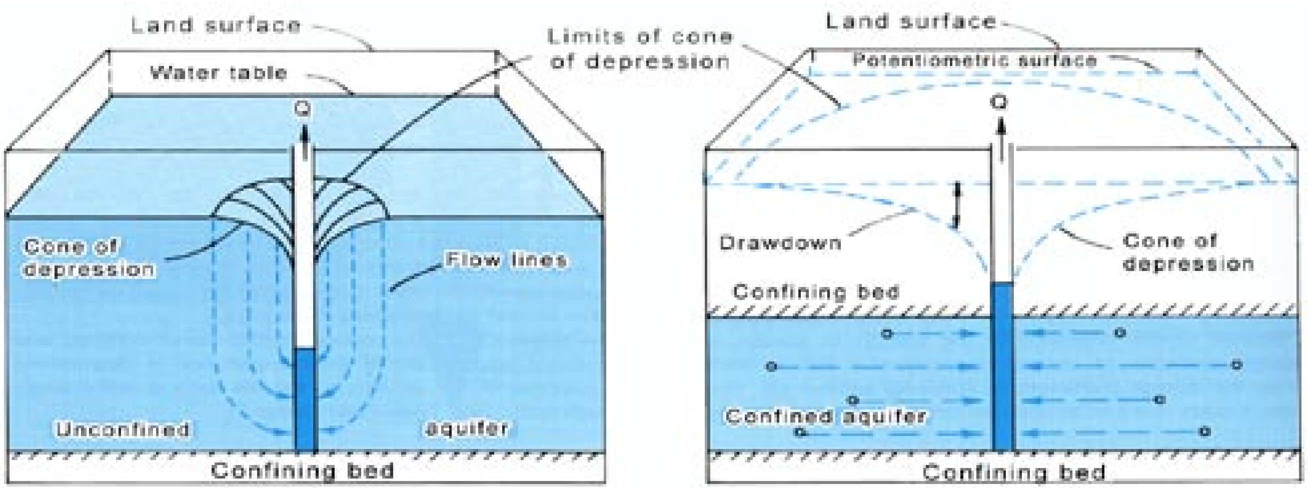
Automated water collection and satellite transmission instrumentation. Photograph from USGS archives.

Chapter 15

Cone of Depression

Many people have heard the term "cone of depression" in discussions concerning the pumping of ground water. In this chapter, cones of depression and how they occur in different settings will be discussed.

A cone of depression occurs in an aquifer when ground water is pumped from a well. In an unconfined (water table) aquifer, this is an actual depression of the water levels. In confined (artesian) aquifers, the cone of depression is a reduction in the pressure head surrounding the pumped well.

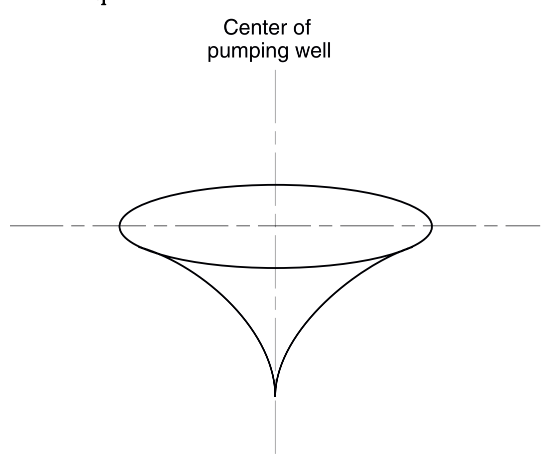


Source: Heath, 1989

When a well is pumped, the water level in the well is lowered. By lowering this water level, a gradient occurs between the water in the surrounding aquifer and the water in the well. Because water flows from high to low water levels or pressure, this gradient produces a flow from the surrounding aquifer into the well.

As the water flows into the well, the water levels or pressure in the aquifer around the well decrease. The amount of this decline becomes less with distance from the well, resulting in a conical-shaped depression radiating away from the well. This, in appearance, is similar to the effect one sees when the plug is pulled from a bathtub. This conical-shaped feature is the cone of depression.

The size and shape (slope) of the cone of depression depends on many factors. The pumping rate in the well will affect the size of the cone. Also, the type of aquifer material, such as whether the aquifer is gravel, sand, silt, fractured rocks, karst, etc., will affect how far the cone extends. The amount of water in storage and the thickness of the aquifer also will determine the size and shape of the cone of depression.



Source: Alley and others, 1999

As a well is pumped, the cone of depression will extend out and will continue to expand in a radial fashion until a point of equilibrium occurs. This usually is when the amount of water released from storage equals the rate of pumping. This also can occur when recharge to the aquifer equals the amount of water being pumped.

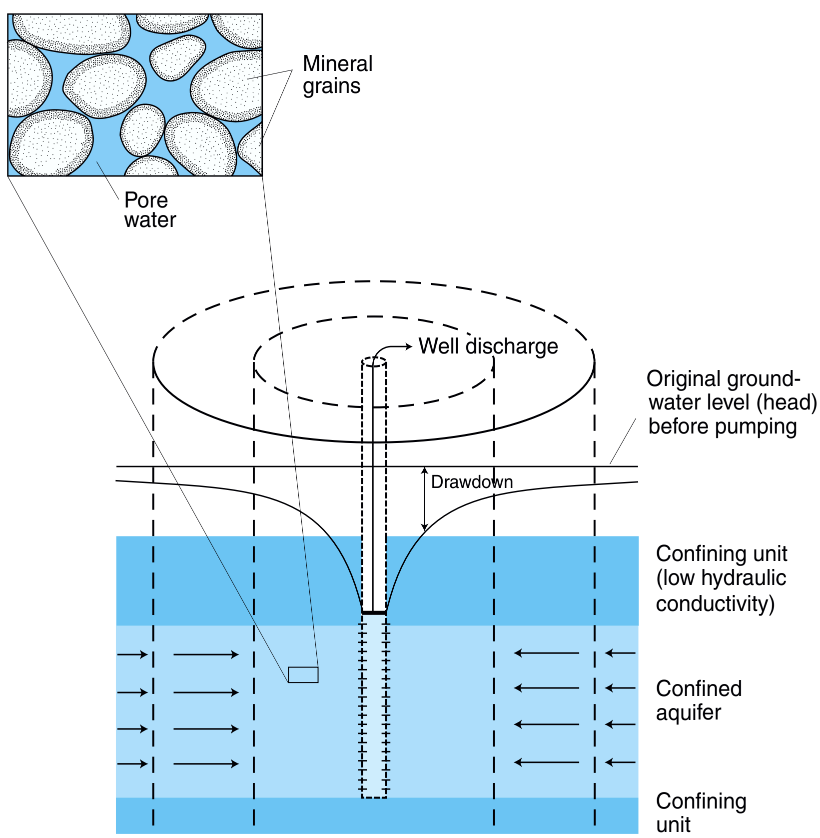
A cone of depression is typically thought of as being a circular feature surrounding the pumped well. However, aquifer characteristics can affect the shape of the cone of depression. For example, if a steep ground-water gradient exists in the area of pumpage, the cone will tend to be shorter in the upgradient direction and elongated in the downgradient direction. This is because the water is already flowing towards the well from the upgradient direction, so the cone of depression does not need to extend as far out to obtain water, whereas the water is flowing away from the well in the downgradient direction, so the cone of depression needs to reach farther to obtain water.

The shape of the cone of depression also can be affected when the cone intersects a source of water, such as a lake or stream. In such cases, water from the lake or stream supplies water to the cone of depression and therefore the cone will not expand as far in this direction. Conversely, if the cone of depression contacts a barrier, such as massive bedrock ridge, a clay body, or the edge of the aquifer, the cone of depression will decline to greater depths in order to supply water to the well.

When two cones of depression intersect one another, they tend to have a combined affect on drawdown and result in water levels or pressures much lower than a single cone of depression would produce. This can be an important consideration when planning well placement and pumping rates. In the case of water supply wells, whether for domestic use or irrigation, wells typically are placed far enough apart in order to avoid intersecting cones of depression. This way, drawdown in the aquifer is minimized. However, in the case of dewatering for mines and landfills where the goal is to lower water levels and pressures, wells often are placed close together in order to reduce head in the aquifer to the maximum amount.

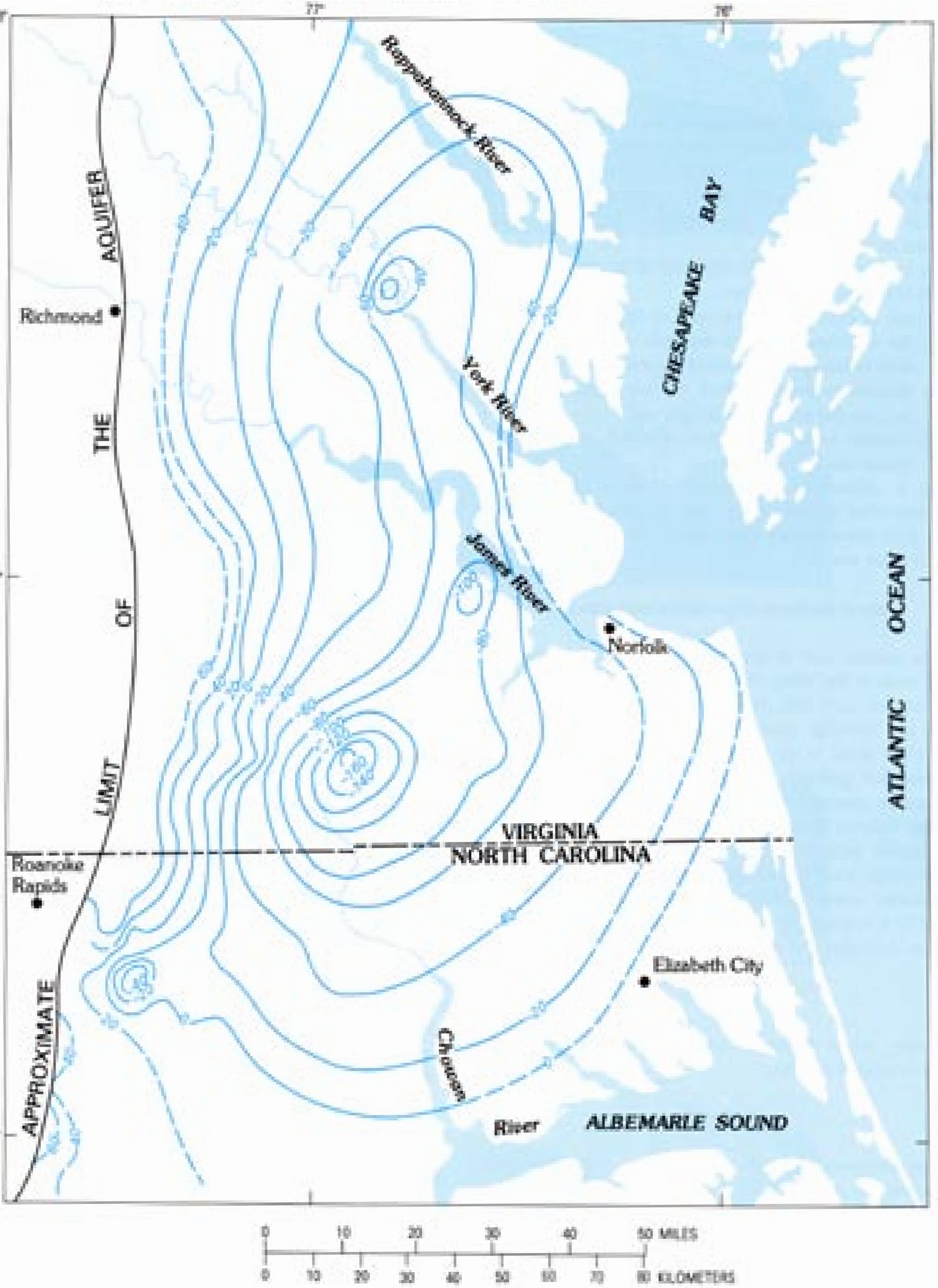
Water levels or pressures can be contoured similarly to elevations on topographic maps. Contour maps often show "bulls-eyes" around pumped wells that represent the cones of depression. In huge municipal wells, these cones of depression often can extend many miles from the pumped well. For many domestic wells, the cones of depression often are too small to even show up on such maps. Again, this really depends on the rate of pumping and the aquifer material.

Cones of depression can be very useful when dealing with contaminant plumes in ground water. Often, a well can be placed near a contaminant plume and pumped at a sufficient rate to create a cone of depression. This cone of depression can act to capture the contaminant flow (essentially pulling it out of the aquifer). The pumped water can then be treated. The use of capture wells has been helpful in protecting water supply wells and for isolating contaminants near spills, landfills, and other sources.



Source: Alley and others, 1999

POTENTIOMETRIC SURFACE OF THE LOWERMOST CRETACEOUS AQUIFER IN SOUTHEASTERN VIRGINIA AND NORTHEASTERN NORTH CAROLINA



EXPLANATION

Water levels are in feet

NATIONAL GEODETIC VERTICAL DATUM 1929

Chapter 16

Aquifer Tests

In previous chapters, aquifer tests have been referred to for making estimates of aquifer properties, such as hydraulic conductivity, transmissivity, and storage. In this chapter, the design of aquifer test will be discussed.

Various methods for doing aquifer tests include slug tests, single well pumping tests, and multiple well pumping tests. In each test, the underlying goal is to stress the aquifer by either pumping water from a well or placing a slug (solid object or volume of water) into a well, resulting in a change in the water level in the well, then measuring the rate of change in water levels as the aquifer returns to normal (static) conditions.

A slug test is a method to test the hydraulic properties of the aquifer immediately adjacent to a well. It involves placing a solid object or volume of water quickly into a well, thus changing the water level in the well. This also can be done by pulling a volume of water out of the well. Either way, once the water level is altered, the time it takes for the water level to return to static conditions can tell a lot about the aquifer surrounding the well.

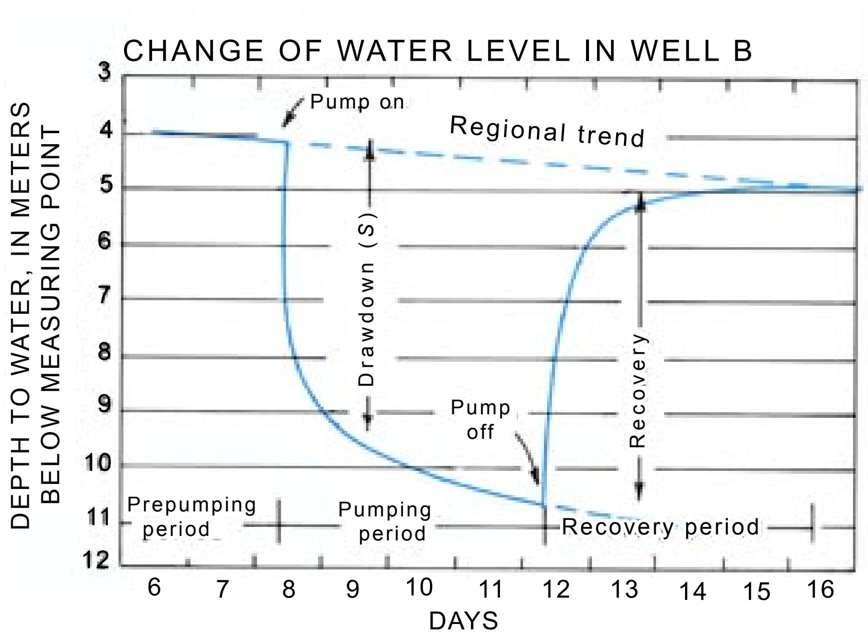
The changes in water levels over time (elapsed time from the initial insertion of the slug) are plotted on a graph. The shape and slope of the curve resulting from plotting water levels versus time can provide information for calculating estimates of hydraulic conductivity and storage.

Slug tests are a quick and inexpensive way to quantify aquifer properties. The limitations of slug tests are that they only stress the aquifer right around the well (zone of influence only extends a few feet from the well). Therefore, slug tests only provide information for that specific location where the well is located and do not give a regional perspective of hydraulic conductivity.

For example, if an aquifer has a lot of fractures or karst, but the well being tested does not intersect these features (it is open to the solid bedrock), then a slug test would give values of hydraulic conductivity for only that part of the aquifer adjacent to the well and would have much lower values of hydraulic conductivity than most of the region. Conversely, if a well intersects a fracture or a cavern and the majority of the aquifer is solid rock, then the slug test would give much higher values of hydraulic conductivity than is typical for the aquifer.

**Aquifer test in Dry Valley.
Photograph by D.L. Berger, USGS**

A single well pumping test is similar to a slug test in that each well is tested independently. For a single well pumping test, a well is pumped at a set rate and water levels in the well are measured until a steady level is obtained. Then the pump is shut off and the rate of recovery in the well is measured. Similar to a slug test, the change in water levels in the well versus time are plotted in a graph. The shape and slope of the plotted curve can provide information that can be applied to calculations for estimating hydraulic conductivity and storage.



Source: Heath, 1989.

A single well pumping test is more expensive to conduct than a slug test because a pump is necessary and it takes more time and manpower, but it has some distinct advantages. The single well pumping test will stress a larger part of the aquifer by pumping from a wider contributing area (extending many feet to even hundreds of feet from the pumped well). Still, only the part of the aquifer contributing to the pumping well is measured, so aquifer variations over distance are difficult to identify.

Multiple well pumping tests are the best means for gathering hydraulic information about an aquifer. To conduct these tests, one well is designated as the pumping well and other wells surrounding the pumping well are used as observation wells. The pumping well is pumped for some period of time (hours or days, typically) and the water levels in the observation wells are measured. Around the pumping well, a cone of depression will occur (drawdown in pressure or water levels due to pumping). The shape of the cone of depression is assessed by looking at water levels in the observation wells.

This type of aquifer test is the best of the three methods because it provides a better, three-dimensional view of how the aquifer reacts to stress. The more observation wells used, the more accurate the assessment. Not only can the hydraulic conductivity, transmissivity, and storage be calculated, but hydrologists also can assess how variations in the aquifer, such as if fractures, bedding, or karst affect ground-water flow velocities and directions (anisotropy) and if the aquifer is different in one area versus another (heterogeneity). In an ideal (homogeneous and isotropic) aquifer, each observation well would be expected to react in a similar fashion (proportional to distance from the pumping well). If this is not the case, then the aquifer test can identify where the aquifer varies and how it differs. This is very useful information in assessing aquifer characteristics and dimensions.

Chapter 17

Evapotranspiration

ET is the combination of evaporation and transpiration. Evaporation is the process of liquid water converting to vapor. Transpiration involves the uptake of water by plants and the subsequent release of vapor from the leaves. Because the two processes typically take place together in the same environment and each are difficult to quantify separately, the two terms are combined into ET.

Discharge for basins in Nevada typically consists of a combination of natural and man-induced components. Ground-water flow out of a basin, ground-water discharge in the form of springs, and ET are the natural components of the hydrologic budget, whereas pumpage of ground water for agricultural uses and human consumption make up the man-induced components. ET is part of the discharge side of the hydrologic budget, where recharge equals discharge, plus or minus a change in aquifer storage.

Evaporation takes place from surface-water bodies, soil moisture, and ground water to depths of several yards below land surface. Sometimes humans help increase the effects of evaporation by pumping ground water for irrigation. The amount of evaporation related to aerial irrigation (spraying) can be a significant proportion of the water withdrawn for this purpose.

Transpiration depends on plant type and density, soil characteristics, root depth, and climatic factors such as temperature, relative humidity, and solar radiation. In Nevada, xerophytes, such as many types of sagebrush, tend to transpire much less water than phreatophytes, which are plants with tap roots reaching the water table. Some studies have actually shown small cones of depression in the water table around phreatophytes because of the removal of ground water by the roots.

Measuring ET is not always easy. In earlier studies, ET was often considered the residual component in the water balance equation after accounting for the known quantities. What this means is that other factors, such as precipitation, streamflow, spring discharge, ground-water flow, pumpage, ground-water levels, and other variables affecting the water balance, were measured and quantified. The unknown, ET, was estimated as the difference between the known recharge and discharge components (plus or minus change in storage). Obviously, this technique does not allow for much confidence in the ET estimates.

Most studies now attempt to quantify ET as a measurable component to the equation. However, many different ways exist to do this, and like most science topics, disagreements and debates occur over which method is the best.

One method to quantify ET is to conduct laboratory experiments that measure transpiration rates for various plants and then apply that information to real world settings. For example, say that three types of plants exist in a certain basin. If the average transpiration for these plants was measured, and estimates of evaporation for bare soils and surface water were made, then aerial photos showing plant coverage could be used to make estimates of ET for the basin.

Dome ET, Amargosa Desert.

Measuring ET in the field can be accomplished using several methods. These methods include dome measurements, weighing lysimeters, and energy-budget calculations. Dome measurements and weighing lysimeters are the most direct methods for estimating ET.

The dome method involves placing a large plastic dome over a representative area of plants and soils. The actual amount of water released as ET is measured. This method provides a short measurement (minutes), so it essentially takes a "snapshot" of the ET.

Weighing lysimeters are, in their simplest form, containers of soil, buried flush with the ground surface, that are weighed periodically. Vegetation that ideally represents the surrounding area is planted in the lysimeter at land surface. Use of weighing lysimeters requires measurements of weight changes that result from ET (weight loss) or precipitation (weight gain).

Two other methods for measuring ET in the field involve the Bowen-ratio and eddy-correlation methods, which are based on energy-budget calculations associated with the process of ET. During the ET process, energy is used to convert water from liquid to vapor and transfer the vapor to the atmosphere.

In the environment, energy is partitioned by the energy budget into four principal components: (1) net radiation, the sum of all incoming and outgoing radiation; (2) subsurface heat, the amount of energy stored in the soil or water; (3) sensible heat, the amount of energy that heats the air directly above the soil, plant canopy, or water surface; and (4) latent heat, the amount of energy consumed by the process of ET.

Very sophisticated instrumentation is used to measure the four different energy components. The instrumentation is deployed in the field of study for up to several years. By solving the energy budget based on the measurements of the four energy components, estimates of ET can be derived.

It is important to have a good understanding of ET in order to make accurate assessments of water budgets for any given basin. For example, a USGS study was done in Ruby Valley National Wildlife Refuge in 2000 where in 1 year about 89,000 acre-feet (about 29 billion gallons) of water was lost to ET.

ET Station in Ruby Valley. Photograph by D.L. Berger, USGS.

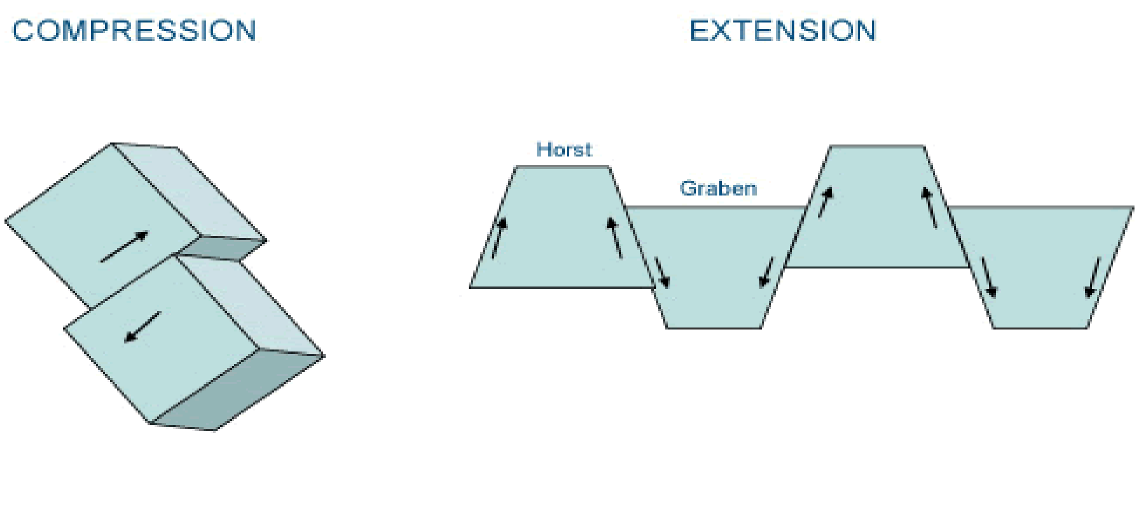
Chapter 18

Geology of Eastern Nevada and the Occurrence of Ground Water in the Carbonate Aquifer System

It is difficult to summarize the geology of much of Nevada in a short chapter because it is quite complex. However, it is important to understand the geology because it is what controls the occurrence and movement of ground water in this region. Therefore, this chapter will take a broad view of regional geology in eastern Nevada, where extensive ground-water resources are the focus of much interest and study. Many of the concepts concerning eastern Nevada apply to other parts of Nevada.

Eastern Nevada is part of the Great Basin, which is a physiographic area that covers most of Nevada and western Utah, stretches from the Wasatch Range near Salt Lake City to the Sierra Nevada, and extends slightly into Oregon, Idaho, and California. This large area is comprised of hundreds of smaller basins, each surrounded by topographic high areas, or ranges, and is known as the Basin and Range Province. It is best described as a collection of north-northeast trending mountain ranges separated by broad alluvial desert basins.

A complex series of events created the Basin and Range topography (the physical surface features of a region). In the geologic past, a shallow sea covered much of the present Western U.S. Thick sequences of sediments were deposited offshore of the western margin of the ancestral North American coast, which was within present-day Utah. Later, this area became continental and different types of sediments were deposited across the region. Compression resulted in thrust faulting that pushed various masses of rock on top of one another in the western part of the present Basin and Range, resulting in complex stacks of different rock types. In eastern Nevada and western Utah, the rock types mainly remained marine sediments. The topography of the Basin and Range resulted from later uplift and extension (spreading) that pulled land apart. This extension resulted in some geologic blocks dropping relative to other geologic blocks. These dropped blocks form the basins, whereas, higher blocks form the ranges.



On the previous page, the image on the left shows thrust faulting, which can occur when two land masses are pushed together (compression). The image on the right shows features referred to as horst and grabens. These are German terms for ridges and trenches and these can occur when land is pulled apart (extension) and some blocks of land drop down relative to other blocks of land. The result is the basin and range topography of Nevada.

The geology of eastern Nevada consists of consolidated carbonate (such as limestone) or noncarbonate rocks, and basin fill. The carbonate rocks typically are fractured and jointed and these features have been widened by the solution of the rock by ground water (same process that forms caves and caverns). These rocks can be quite thick, with estimates ranging between 5,000 and 30,000 feet. This combination of high permeability due to fractures, joints, and solution features, in addition to the large thickness, is why the carbonate rocks make up an important aquifer in eastern Nevada. However, the connection of the carbonate aquifer from one basin to another basin is not well defined for many areas. Some geochemical evidence indicates that ground water moves more than 100 miles between basins in eastern Nevada.

The noncarbonate rocks in eastern Nevada include a wide range of rock types, including metamorphic (such as gneiss or schist) and igneous rocks (such as granite), fine-grained sedimentary rocks (such as shale and siltstone), and volcanic rocks (such as basalt). For the most part, these noncarbonate rocks tend to act as barriers to ground-water flow because of their low permeability. The exception would be some of the volcanic rocks, which can be aquifers if the conditions are right. In Fallon and in parts of southern Nevada, volcanic rocks serve as sources of water for users. The consolidated carbonate and noncarbonated rocks are the bedrock that forms the mountain ranges and underlies unconsolidated basin-fill sediments in the valleys.

The third type of geology is basin fill. The unconsolidated sediments (such as sand, gravel, and clay) that were eroded off the mountains were deposited in the basins by streams. The thickness of basin fill really depends on the local geology (how resistive the surrounding mountains are to erosion) and the depth of the basins between the ranges. The thickness of basin fill in eastern Nevada can range between thin deposits to greater than 10,000 feet. The basin fill also acts as an aquifer for much of the region and most ground water used in eastern Nevada is pumped from basin-fill aquifers. The degree of ground-water flow from basin fill in one basin to another depends on the topography (is the basin fill isolated or does it extend between basins where one basin is higher than another?) and bedrock geology of the ranges (can water move through the ranges or is it impermeable?). Just like the geology of the Basin and Range, the hydraulic connection between basins is highly variable.

An important aspect of the hydrogeology of the Basin and Range is the connection between the basin-fill aquifers and the carbonate aquifers that underlie some basins. This is important because it can affect recharge to the carbonate aquifers. Plus, it can mean that factors affecting one aquifer, such as pumping stresses, may affect other aquifers. This can go both ways, where pumping in the basin-fill aquifers may affect ground-water recharge to the underlying bedrock aquifer, and pumping from the bedrock aquifer may affect water levels in the overlying basin-fill aquifers. There is no simple answer to this because each basin is unique and different. Specific research on a particular basin or group of basins is needed to truly understand how the hydrology will be affected by different stresses.

Most recharge to aquifers in the Basin and Range originates from precipitation that falls in the higher mountains. Water in the form of rain and snowmelt can percolate into fractures in the bedrock or runoff to streams that lose their flow to aquifers in the valleys. Ground-water discharge from a basin typically occurs as ET, ground-water flow out of a basin, springs, or pumpage for irrigation, domestic, municipal, or mining/industrial needs. Pumping of ground water can affect surface-water supplies (either streams or springs) because declines in ground-water levels could increase stream losses and decrease spring flows.

Chapter 19

Alluvial Basins

In the discussion of the hydrogeology of eastern Nevada in the previous chapter, the hydrologic conditions were greatly simplified. For the most part, the hydrogeology was broken into bedrock, which consists of either carbonate rocks (such as limestone) or noncarbonate rocks, and alluvial (basin-fill) deposits that occupy the basins between mountain ranges. The reality is that the alluvial deposits are complex and can greatly affect ground-water movement.

Alluvial deposits, also referred to as alluvium, are sediments such as gravel, sand, silt, and clay, which have been transported by water flowing off of the mountains. When the Basin and Range originally formed, some blocks of rock were uplifted, forming the mountain ranges, whereas other blocks were down dropped, forming the basins.

Following the formation of the mountains and basins, erosion began to affect the rocks. Geologists refer to erosion as weathering and it consists of breaking up of rock by various processes, such as frost wedging (where water gets into cracks in the rocks and then freezes, which makes the water expand and break up the rock), water erosion from rain and snowmelt, wind erosion, landslides and debris flows, plant roots growing into cracks in the rocks and causing spreading of the openings, and many other processes.

Once the rock has been weathered, then gravity and runoff of rainfall and snow melt carry the rock debris downslope to valleys and canyons. Larger streams in these valleys then can carry the rock debris down the mountains and out onto the basins. When the streams are confined by the steep walls of the mountain valleys, the water moves quickly and can carry a lot of sediment. Once the streams flow out onto the basins, they spread out and lose their energy, resulting in the sediment loads being deposited. This is why we tend to find the larger sediments, such as boulders and gravels, near the mouths of the valleys and canyons, and the finer sediments further out on the basin floor. As the energy in the streams decrease, the ability to transport heavier sediments also decreases.

Because the streams are confined in these valleys while flowing out of the mountains and then spread out as they flow onto the basins, the sediments get deposited in a triangular fashion with the top of the triangle at the mouth of the valley and the base of the triangle onto the basin. This is referred to as an alluvial fan, because it has the shape of a fan. In a similar manner, if the fan occurred into a water body, such as a lake or ocean, instead of the basin floor, then it would be called a delta. If you look at the Mississippi or Nile Deltas, one will see these also have a similar triangular shape.

Many of the basins in Nevada are covered in numerous and overlapping alluvial fans. Over time, these fans have filled the basins with sediments transported from the mountains. Because the fans tend to have coarser sediments near where the streams enter the valleys and finer sediments further away, many basins have finer sediments near the centers of the basins and coarser sediments near the margins. As one can imagine, the difference in sediment size can affect the ability of water to move through the basins. Larger sediments tend to have higher hydraulic conductivities, whereas finer sediments tend to have smaller hydraulic conductivities. The ability of the sediments to store water also is affected by the grain size (porosity).

This all seems simple enough, but one also needs to consider that most streamflow from the mountains to the basins is not continuous and generally occurs following rainfall and snowmelt. Therefore, the transport of sediments to the basins occurs in pulses. Plus, each rainfall and snowmelt event is different in magnitude and sometimes the streamflow is small and other times there are "gully-washers" or significant floods. Because of this, the size and distance sediments are transported on the basin floor is different with each event.

The result of the different depositional events onto the basin floor is a layering of the alluvial deposits, where coarse and fine sediments may alternate in a series of horizontal beds. This really can alter how ground water moves vertically through the alluvium.

During the times between alluvial deposition, wind action can transport and deposit fine-grained sediments around the basins. Wind-deposited sediments are referred to as eolian deposits (such as sand dunes). Soils also can form on the basin floors. Alluvial deposits interbedded with eolian deposits and soils can make vertical ground-water movement complex.

Lakes that form in some basins during wetter and cooler times can deposit layers of clay and silt (and salt when the water evaporates) in the basins. Lake deposits are referred to as lacustrine sediments. These clay and silt deposits act as local confining units to the alluvial sediments and can greatly restrict ground-water movement. During the Pleistocene Epoch (the last ice age ending around 8,000 to 9,000 years ago) many of the basins in Nevada were covered by huge lakes. This is why many archeological sites, which focus on early humans in Nevada, are found around the edges of basins…they lived along the shores of the lakes. These huge lakes left thick clay and silt deposits in many basins, causing complex conditions for the hydrogeology of the basin sediments.

Rivers that flow across many basins also can remove, transport, and deposit sediments. These are referred to as fluvial deposits. Meandering rivers can incise channels across the basins. As these rivers continue to meander and change course, the abandoned channels can become filled with sediments. These "cut and fill" features can cause localized variations in ground-water flow conditions. In some places, filled channels, if filled with gravel, can be considered good local aquifers. In other areas, if the channels are filled with fine sediments, these can inhibit ground-water movement.

Many other geologic conditions can affect the hydrogeology of alluvial basins, but it is clear from just these examples that basins in Nevada are typically quite complex. Hydrogeologists use various tools, such as drilling into the sediments and collecting cores, geophysical techniques such as ground-penetrating radar and seismic profiles, and geologic mapping to try and identify where these variations in the alluvium occur. It is important to understand the conditions in the alluvial basins in order to better evaluate the overall hydrogeology of the basin and range system.

Chapter 20

Geophysics

One goal of hydrogeologists is to understand the subsurface. In other words, to have a good idea about the types and thicknesses of rocks beneath land surface, the depth to water, the direction of ground-water flow, and how the geology affects ground-water storage and movement.

Hydrogeologists often rely on geologic information obtained from drilling wells, outcrops of the bedrock at various locations, stream channels that cut into the land surface, and road cuts for highways and railroads to provide clues as to the subsurface geology. But, these sources of information usually are sparse. Scientists often need to speculate and theorize about geology between well sites and other exposures.

One way to gather information when physical access to the subsurface is not available is to use geophysical methods. These methods give a glimpse of what lies below the surface without actually drilling into the ground and collecting geologic samples. It is similar to how doctors use x-rays and ultrasounds to see what is inside a body without actually operating. Considering the cost of drilling, geophysics, which is usually quick and less expensive, becomes a really attractive tool for helping hydrogeologists.

As the name implies, geophysics is the study of the physics of the Earth and its surrounding atmosphere. Geophysical techniques are used to detect discontinuities in the Earth, where one area or region differs significantly from another in some property. Identifying discontinuities can help hydrogeologists locate changes in the geology, where ground water occurs, and even buried features and objects below the Earth's surface.

A number of geophysical methods exists and each has advantages. In the broadest sense, these methods can be grouped into solid earth geophysics, which deals with earthquakes and understanding the dynamics of the Earth, and applied (exploration) geophysics, which consists of methods used to explore the Earth; these are discussed in this chapter.

Applied geophysics is grouped into various fields such as gravimetry, magnetic, electrical, electromagnetic, seismic, and radioactivity. All of these techniques can be used from the air, on the ground, or in boreholes.

Gravitational surveys are useful for identifying changes over large areas. The mass of rocks affects the value of the acceleration of gravity. Therefore, as mass changes, so will the gravity measurements. This is useful because rocks such as granite and gneiss have larger gravity values than unconsolidated sediments, such as sand and gravel. By measuring changes in gravity, changes from one type of geology to another can be mapped. This information also can help map buried features, such as large igneous rock bodies, channels filled with sediments, or caverns in limestone.

Magnetic surveys measure differences in the Earth's magnetic field caused by magnetic materials in the Earth's crust. Because sedimentary rocks, such as limestone and shale, generally are not magnetic, using magnetic surveys can help hydrogeologists detect the depth to the magnetic basement rocks. Also, in some areas, basalts (volcanic rocks which may be aquifers in some places) may have magnetic minerals, whereas the surrounding sediments and rocks possibly are nonmagnetic. Therefore, magnetic surveys can help identify the extent of the basalt, and therefore the extent of the aquifer. In eastern Nevada, magnetic surveys have been used to help identify the locations of igneous intrusions into the carbonate rocks.

Electrical methods consist of sending electric current into the ground and measuring the conductance and resistance in the Earth materials. This method is often used in borehole surveys, where probes are lowered down boreholes and changes in the electrical properties are measured along a vertical profile. Changes in the rock type, density, and fluid properties, such as salinity and temperature, can result in variations in the electric signal.

Electromagnetic (EM) surveys involve sending short electromagnetic waves into the Earth and measuring the time of return. Usually, this method is mobile, where the sending and receiving units are mounted on a vehicle and can be driven across an area of interest or lowered into a borehole. EM has been very useful in identifying intrusions and buried channels in the shallow subsurface, as well as mapping shallow bedrock geology. From the surface, most EM techniques do not penetrate to large depths, so the method has limitations for deep systems such as in the Basin and Range of Nevada.

A geophysical method that has been used a lot recently is temporal or microgravity. Microgravity measures very small changes in gravity directly beneath the instrument. As mentioned earlier, gravity can be affected by the mass of the geologic units. Likewise, the change in ground-water storage in an aquifer can affect the gravity. Therefore, by measuring the microgravity over time in numerous locations over an aquifer that is being pumped, changes in storage in the aquifer (declines or rises in the amount of water in storage) can be measured. This is useful in identifying where aquifers are affected by pumpage and in determining aquifer characteristics such as specific yield and porosity.

Seismic reflection and refraction methods use a system where either a hammer on a metal plate on the surface or small explosive charges are set off, which send seismic waves into the subsurface. On the Earth's surface, numerous stations with geophones (detectors to measure the energy waves) are set up at various distances from the explosive charge. The time it takes for the seismic waves to return from the subsurface, where they are reflected or refracted off of different geologic layers, can tell scientists the depth of the geologic layers and the type of materials the waves are passing through (the speed of the waves will vary depending on the geologic material or density). Likewise, the pattern of the waves and when and where the waves return to the surface (distance from the explosive charge) also will be affected by the depth of the layers and the type of geology that is refracting the waves. These techniques are used frequently in the oil industry to detect stratigraphic traps where oil is found.

Radioactive methods involve both the measurement of natural radiation and the induction of radiation from an energy source to gather information about the geology. Most commonly used methods involve lowering a geophysical tool down into a borehole and measuring how signals change between different geologic layers. Passive methods, which measure existing radiation, include measuring natural gamma and other radioactive emissions from geologic materials. Nonpassive methods involve the application of a radioactive energy source (such as gamma-gamma and neutron emissions) and the measurement of how this energy is either backscattered or moves through the surrounding rocks.

Tomography is another borehole geophysical method that is useful when two drill holes are in proximity of each other. At various depth increments, an energy source, such as seismic or radar, can be lowered down one hole and the signal measured at various depths in the other hole. This gives a really good profile of the entire geologic sequence that occurs between the two holes.

One interesting use of geophysics is to identify buried tanks and drums, and to outline the extent of contaminant plumes, all which have aided in the clean-up efforts of contaminated sites. Another use has been in forensic geology, where geophysics has been used to help locate buried bodies and disturbed geology. This technology has been used to identify buried bunkers in wartime and has helped to find hidden combatants and elusive leaders.

Many other geophysical methods are used on a regular basis but are not mentioned in this chapter. The main point is that geophysics provides a valuable tool for understanding the subsurface of the Earth without having to drill numerous holes. Like all tools in geology, geophysics by itself is useful but has its limitations. To truly understand a geologic or hydrologic system, it is best to have a variety of tools, such as boreholes, field mapping, geochemistry, and geophysics, which either support the conclusions of each other or possibly identify where additional study is needed.

Chapter 21

Water Quality

The quality of water is dependent upon the types and concentrations of dissolved constituents. All natural waters have some dissolved components. Rain and snow form in the atmosphere and absorb gases found in the air. In addition, rain and snow form as condensation on dust particles, so the composition of the dust also can affect the precipitation. Once the rain or snow reach the Earth's surface and either runoff as surface water or infiltrate as ground water, they begin to interact with the soils, rocks, plants, and other natural and manmade items they encounter. The longer water stays in contact with something, the more probable that the chemistry of the water will be affected by the interaction.

Just because water contains other chemicals and compounds certainly does not mean the water is contaminated or harmful. In fact, many of the chemicals dissolved in water are important for human health, such as calcium, magnesium, and iron. As many have pointed out in the past, often the only difference between a healthy supplement and a poison is the dose. In small quantities, many things have beneficial qualities. In large quantities, the same things can be harmful or deadly.

Scientists typically evaluate natural water quality based on major ions, minor ions, and trace elements. Major ions include calcium, magnesium, potassium, sodium, carbonate, bicarbonate, chloride, and sulfate. They often will refer to water by these major ions, such as a calcium-bicarbonate-type water or a sodium-chloride-type water. These constituents usually are dissolved by the water as it interacts with soils and rocks.

Water-quality sampling in the Lake Tahoe Basin. Photograph by Emil Stockton, USGS.

As one would expect, water in a limestone aquifer typically is a calcium-bicarbonate-type water (limestone is made up of calcium carbonate). Water in shale might be a sodium-sulfate-type water. The soils and geology can strongly influence the chemistry of the water. And, the longer water is in contact with a rock type, the more it can dissolve the rocks and concentrations will increase. Therefore, not only do scientists look at what is dissolved in water, but also how much is in solution (often described in concentrations of milligrams per liter or micrograms per liter).

Minor ions include such things as iron, manganese, fluoride, nitrate, strontium, and boron. Many of these minor ions, although typically in lower concentrations than the major ions, can be important for human health but also can be undesirable or harmful in high concentrations. For example, iron is a necessary mineral for humans, but in high concentrations, iron can cause discoloration in water and mineral deposits in pipes, sinks, bathtubs, and toilets. Nitrate in high concentrations can have harmful health effects on humans, especially in babies. Fluoride is an additive to water in many locations because of its benefit to healthy teeth, but in high concentrations, it can be harmful.

Trace elements usually are present in natural waters in very low concentrations; a few micrograms per liter (parts per billion) or less. Trace elements consist of a wide range of chemicals, including arsenic, lead, selenium, cadmium, and chromium. Typically, trace elements can be harmful at high concentrations. In Nevada, arsenic occurs in most natural waters because of the geology. The USEPA has recently lowered its MCL for arsenic in public water supplies from 50 micrograms per liter to 10 micrograms per liter. Many Nevada communities will have a difficult time finding ways to meet this new standard. Selenium is another element that benefits human health in low concentrations, but at higher concentrations, it can be toxic.

Other ways scientists describe water quality includes characteristics, such as hardness, pH, and dissolved solids. Hardness is a measure of the amount of calcium and magnesium in water and its affects on the ability of the water to lather with soap and to cause scaling on pipes. The hardness of water is classified in milligrams per liter of calcium carbonate as 0–60 (soft), 61–120 (moderately hard), 121–180 (hard), and more than 180 (very hard). The pH of water indicates its reactive characteristics. Low values of pH (below 4) indicate acidic water that can corrode metals. High values of pH (above 8.5) indicate alkaline water that can result in scaling when heated. Dissolved solids are the total amount of minerals dissolved in the water. This is measured in milligrams per liter (roughly parts per million) and water below 500 milligrams per liter is considered good. The classification for dissolved solids (in milligrams per liter) is less than 1,000 (fresh), 1,000–3,000 (slightly saline), 3,000–10,000 (moderately saline), 10,000–35,000 (very saline), and more than 35,000 (briny). Seawater is about 35,000 milligrams per liter dissolved solids.

So, evaluating the composition of water can tell a lot about its water quality. Of course, many other constituents can affect the quality of water, such as bacteria and pollution, but these will be discussed in the next chapter.

Chapter 22

Contamination

Water naturally contains a variety of dissolved components and although this helps classify the type of water, it does not necessarily mean the water quality is poor. In fact, many of the dissolved components in water are useful and beneficial to humans.

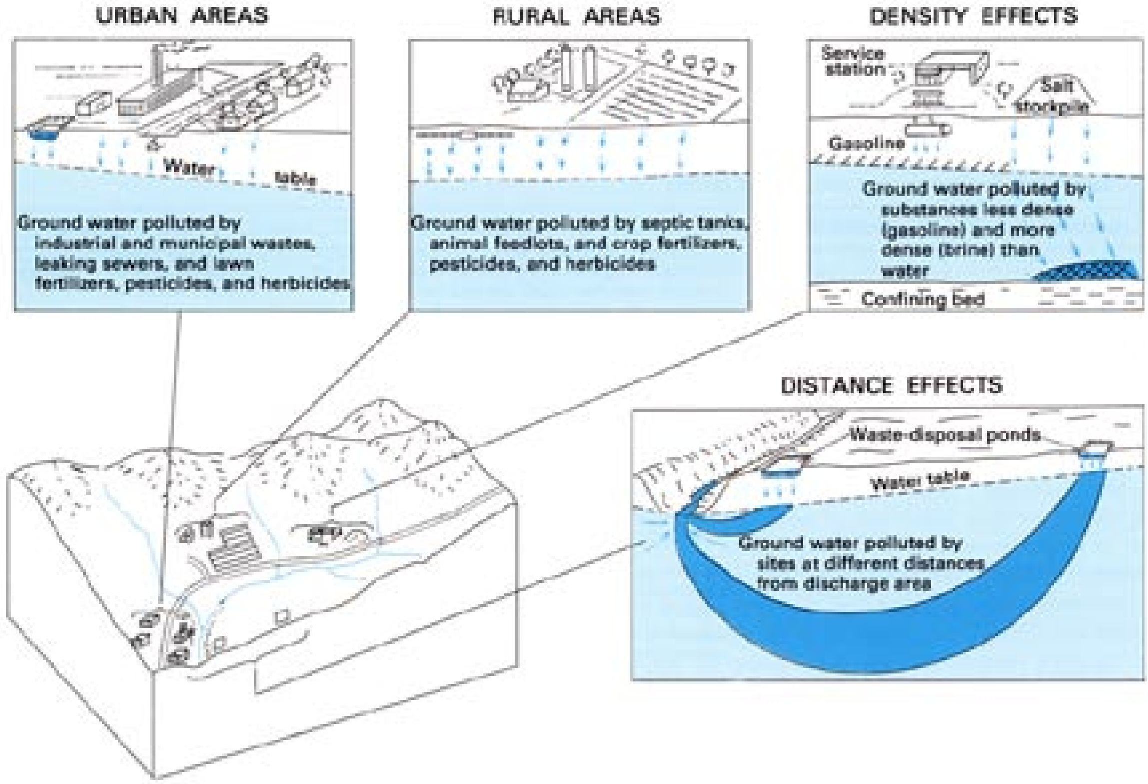
Contaminated water, however, is a different story. Contaminated or polluted water occurs when human activity changes the natural water quality making it no longer fit for use as previously intended and utilized. Just like with the discussion of water quality, the key part of the definition concerns quantity or how contaminated is the water. It is extremely rare that any precipitation, surface water, and shallow ground water have no level of human contamination. In fact, snow samples from the surface of Antarctica and Greenland show trace levels of industrial aerosols and tritium (radioactive hydrogen from bomb tests beginning in the 1950s). Rain and snow in the U.S. typically contains trace amounts of industrial and agricultural chemicals. Does this mean the rain and snow are contaminated? Not necessarily. The precipitation contains contaminants, but usually the levels are low enough to not change how people would use the water.

Contamination of water is related to criteria established by the USEPA. Different standards are applied based on water use, such that water quality for fish habitat will have a different set of criteria than that for human drinking water. These standards are based on the potential effects (toxicity) posed by exposure to certain chemicals. Some chemicals at very low levels can be toxic to humans. Also, some chemicals have adverse effects in small doses or exposures (acute exposure) compared to others which require long-term exposure (chronic exposure), often over many months or years.

Based on the risk of known chemicals, the USEPA has developed drinking water standards as part of the Safe Drinking Water Act. Under this act, many known chemicals have been classified and human exposure quantified by MCLs. MCLs provide maximum amounts of exposure to any certain chemical above which there are potential human health risks. These standards are based on the best science available, but we need to keep in mind that many chemicals are relatively new to the environment (and to humans) and their long-term health effects may need more research and real-world data collection to better understand how these chemicals actually affect people.

Contamination of water can be from various sources. In most of rural Nevada, potential sources include chemicals in precipitation, agricultural chemicals, urban and domestic contamination, mining practices, and various spills. Chemicals in precipitation can be industrial and agricultural chemicals carried as dust and particles in clouds that get deposited with rain and snow. Winds can pick up dirt that has chemicals with it and carry these contaminants to the atmosphere. Industrial and urban (cars) exhaust goes into the atmosphere and can be carried for long distances by the winds before being deposited. An example of this is acid and mercury found in lakes in relatively pristine parts of the Appalachian Mountains that were carried by the wind and deposited in rain and snow. What happens downwind from a location, even hundreds of miles downwind, can ultimately affect the water quality at this location.

Many studies have shown that agricultural chemicals (pesticides, herbicides, and fertilizers) are showing up in surface water and ground water across the country. Often, these chemicals are found in direct association to where they are applied (such as in shallow ground water beneath a farm field). However, rain and snow also carry some levels of agricultural chemicals. One thing scientists are now researching is not only the occurrence of these chemicals in water, but also how these chemicals change in the environment.



GROUND-WATER POLLUTION OCCURS IN BOTH URBAN AND RURAL AREAS AND IS AFFECTED BY DIFFERENCES IN CHEMICAL COMPOSITION, BIOLOGICAL AND CHEMICAL REACTIONS, DENSITY, AND DISTANCE FROM DISCHARGE AREAS

Source: Heath, 1989

Agricultural chemicals are designed to breakdown in the environment. However, these chemicals breakdown into different chemicals. Most of these "breakdown products" typically are harmless, but some are now being studied because of potential health risks.

Urban and domestic contamination can be a wide variety of substances. One of the most prevalent in Nevada is nitrate from septic systems. High nitrate levels can be dangerous for all humans, but especially for babies. Other sources of contamination include, but are not limited to, leaky underground storage tanks at gas stations, storm runoff from streets into drains, lawn care products, automotive exhaust, landfills, road salt, cemeteries, car washes, and other potential releases of chemicals. One of the sources of contamination under recent study is what we call emerging contaminants, specifically pharmaceuticals and personal care products. Such things like antibiotics and other medicines are getting into the environment from human and animal waste discharge and from people dumping extra medicines into sinks and toilets. These products can produce resistive bacteria in the environment. Personal care products, such as skin and hair products, soaps, detergents, and even caffeine from beverages, are being detected in the environment.

Mining practices can be an important source of potential contamination in Nevada because of the large number of mines (present and abandoned). Contaminants, such as arsenic, are associated with mines because of ore processing and exposure of rock debris to weathering. Acid-mine drainage from sites has been shown to affect water quality in runoff and ground water near mines. Mercury has been widely used in Nevada to extract metals such as gold and silver from ores. The mercury can get into the environment and have potential human and aquatic health effects. For example, mercury from mining has contaminated sediments in the Carson River. Mining also uses cyanide for leaching gold and silver from ores. Spills and leaks of cyanide can cause contamination and has been associated with fish kills in some mining areas of the country.

Spills are a common occurrence for surface-water and ground-water contamination. Most people are familiar with the Exxon Valdez oil spill. Spills can happen wherever potential environmental contaminants are stored or transported. Trains and fuel trucks can become damaged (usually through collision or human error) and leak large quantities of contaminants into streams or into the ground. People often think about these large spills when talking about contamination, but many spills can be smaller and still quite harmful. Some folks dump old paints and fuels from their homes and farms into drains or into the backyard. These contaminants get into the water supply and cause damage. Some people drain their engines directly onto the ground when doing oil changes. This too can get into drinking water supplies. Often normal human activities can be the cause of many spills and degradation of the water supply for a community.

As one can see, water can become contaminated in a number of ways. Some things can not be controlled locally (such as pollution that gets into the air and carried by the wind). These require State or Federal regulations to control. Other things can be controlled, such as what is put into the ground, down drains, or on yards. The most important thing to keep in mind when considering contamination is that everyone lives downstream (in some form or another, even if talking about air contamination) from someone else. What one does to one's yard, one's land, and one's city can affect many surrounding people and those downgradient.

Potential source of surface-water contamination. Photograph from the USGS Toxic Substances Hydrology Program, Midcontinent Herbicide Reconnaissance study <http://toxics.usgs.gov/photo_gallery/ag_chemicals.html>.

Fish samples collected as part of the USGS National Water-Quality Assessment Program. Photograph by M.R. Rosen, USGS.

Chapter 23

Isotopes

In the next two chapters (chapters 23 and 24), the use of isotopes to identify sources of water and for age-dating water will be discussed. The term "isotopes" sounds very technical, but the concepts are quite simple.

Everything in the world is made up of atoms. More than 100 different types of atoms occur naturally in the world. Each atom is made up of smaller components called protons, neutrons, and electrons. The combination of these smaller components is what makes atoms different.

For example, most people are aware that water is referred to as H_2O. This means that water is made up of two hydrogen atoms and one oxygen atom. Every atom has its own weight, as determined by the number of protons and neutrons (electrons really do not have much weight compared to the protons and neutrons). Hydrogen has one proton and one electron, so the weight is 1. Oxygen has 8 protons, 8 neutrons, and 8 electrons, so its weight is 16.

This relation of the number of protons and neutrons making up the atomic weight works for every atom and it is what makes each type of atom different from other atoms. For example, gold has 79 protons and 79 neutrons, aluminum has 13 protons and 13 neutrons, etc. Of course, the numbers of electrons are equal, but because these do not weigh much, they can be ignored in this discussion of atomic weight.

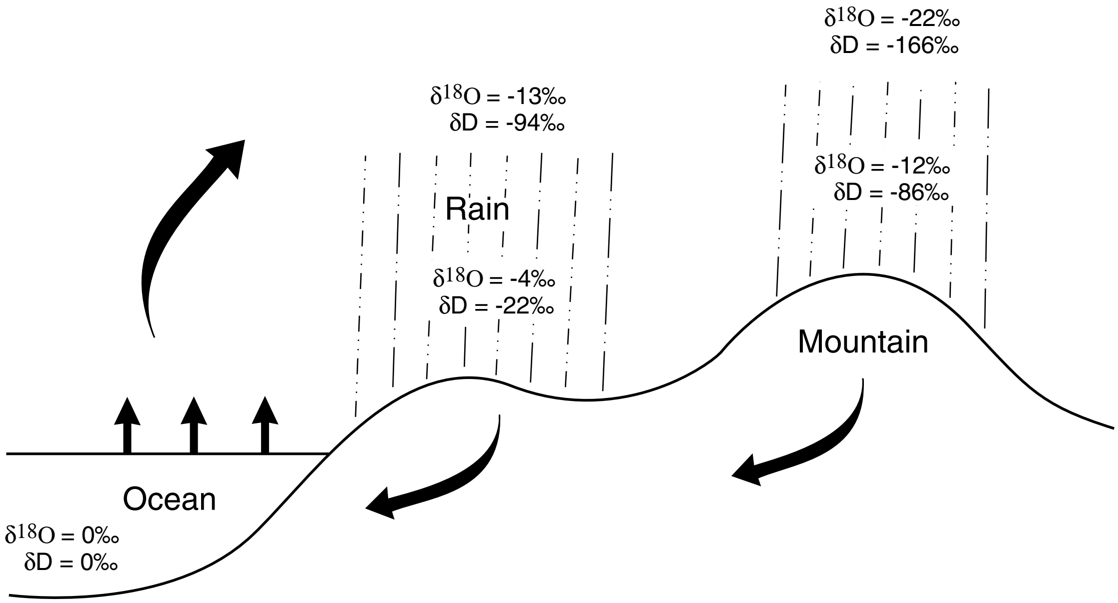
However, nature likes to throw curve balls. In many cases, atoms occur with additional neutrons. This makes these particular atoms heavier than those with equal numbers of protons and neutrons. Atoms with extra neutrons are called isotopes. In the case of hydrogen, there is an isotope with one proton and one neutron. This is called deuterium and it has a weight of 2. Oxygen has an isotope that has 8 protons and 10 neutrons, which has a weight of 18. This does not have a fancy name, rather it is referred to as oxygen-18. In nature, these isotopes of hydrogen and oxygen make up only a small fraction of all of the hydrogen and oxygen, but their occurrence is most important to scientists.

If all water in the hydrologic cycle contained hydrogen, deuterium, oxygen, and oxygen-18, including water held in clouds, the ocean, ground water, etc., then how these atoms get distributed becomes really important.

For example, clouds have water vapor made up of all four of these atoms. As clouds move inland from the oceans and get pushed up over mountain ranges, the clouds will begin to drop their moisture (which is why there is so much rain in Seattle, which is west of the Cascade Mountains, compared to dry Spokane , which is east of the mountains). It seems logical that the heavier atoms (deuterium and oxygen-18) would fall out first and the lighter atoms would hang in there longer.

This is exactly what happens. Heavy isotopes of water tend to drop as rain and snow at lower altitudes and the lighter atoms get deposited further up in the mountains. The same works for temperature. The warmer the temperatures, the heavier the atoms that the clouds can hold. If the atmosphere becomes cooled, the heavier atoms will fall out first. Not only do we see heavier atoms precipitated at lower elevations, but the same generally is true for lower latitudes (the precipitation has lighter isotopes with distance from the equator).

The way isotopes behave really is useful to hydrologists. The ratio of hydrogen to deuterium and the ratio of oxygen-16 to oxygen-18, can be used to help identify where the ground water was recharged.



Schematic showing fractionation of stable oxygen and hydrogen isotopes during rainout. Stable isotope values, which compare isotopic ratios relative to ocean water, are expressed in per mil (‰).

Source: Naus, C.A., Driscoll, D.G., and Carter, J.M., 2001, Geochemistry of the Madison and Minnelusa aquifers in the Black Hills area, South Dakota: U.S. Geological Water-Resources Investigations Report 01-4129, 118 p.

In the case of Nevada, if water collected from springs is compared to precipitation samples in the area, isotopes can be used to tell where the water generally recharged the ground water. For instance, if a spring has water with a hydrogen and oxygen ratio that was much lighter than the water collected from precipitation near the spring, it could be concluded that the water feeding the spring came from a higher elevation (higher in the mountains). Likewise, in a large aquifer system, if the water in a well or spring was much lighter than local precipitation, it can be concluded that the recharge is not from local precipitation.

In many ways, isotopes of hydrogen and oxygen provide a "signature" to the ground water. Well or spring water sampled from different sites but with similar ratios may be from the same recharge area. Isotopes alone can not definitely tell this, but in combination with other tools, such as geochemistry, models, etc., one can make some interpretations about where the water was recharged.

Isotopes of hydrogen and oxygen also can be used to look at interpreting climate during the time when recharge occurred. For example, in many deep ground-water basins in Nevada, the water is lighter than present recharge. One conclusion might be that the water flowed in from higher elevations or latitudes, but another conclusion could be that the water was recharged many thousands of years ago during the Pleistocene (last Ice Age) when many basins in Nevada were covered with lakes. This cooler, wetter period in Nevada history may be observable in the isotopes in the ground water.

The science is complex and one must consider many other things. For instance, isotopes in precipitation change with the seasons and winter snowfall typically is lighter than summer thunderstorms. However, this discussion gives a general idea of how the information can be used to understand ground-water flow.

Chapter 24

Radioactive Isotopes

In the previous chapter, stable isotopes, such as the isotopes of hydrogen and oxygen found in natural waters were discussed. These isotopes are used to identify where recharge occurs and generally the flow paths for ground water. This chapter will discuss unstable (radioactive) isotopes and how these can be used to age-date water.

The idea of radioactivity typically scares people. Some people conjure up visions of Three Mile Island or Chernobyl, but most radioactivity occurs naturally in the world and has many uses to humans other than energy generation. One may be surprised how much radioactivity is around us everyday, although the energy levels typically are quite small.

In the previous chapter, the make-up of atoms and how isotopes result from extra neutrons in the atoms was discussed. The number of neutrons in each atom was stable in that it did not change over time. Radioactivity is a little different in that the number of protons and neutrons in an atom continue to change spontaneously until a stable atom is formed. The change in protons and neutrons results in the emission of alpha and beta particles and gamma rays, all of which give radioactivity its dangerous reputation. The alpha, beta, and gamma emissions are what result in human health issues because, in sufficient quantities, they can cause cell damage in the body.

Federal and State agencies monitor and regulate radioactivity in drinking water using established levels for uranium, radium, and gross alpha and beta particles below which it is considered safe to consume. These typically are extremely low levels and most locations in the country meet the standards. Radon may be an exception in Nevada where many ground-water samples show levels exceeding the proposed maximum contaminant level.

Soil-water vapor sampling for determination of tritium in the deep unsaturated zone at borehole UZB-2, Amargosa Desert Research Site.

An important radioactive isotope for hydrologists is tritium. Tritium is hydrogen with two neutrons (remember deuterium is hydrogen with one neutron). Tritium in low concentrations occurs naturally and is formed by cosmic rays interacting with atoms in the upper atmosphere.

However, nuclear weapons testing in the 1950s and 1960s added much tritium to the atmosphere. Large spikes in the tritium concentrations that occur in the environment relate to specific time periods when large and multiple nuclear weapons tests took place. This is very evident when looking at ice cores from Antarctica and Greenland, where annual snow accumulation provides an atmospheric and climatic record for thousands of years before present. In these ice cores, large spikes in the beta activity occur in the ice layers deposited in the 1950s and early 1960s. By this same principle, if one tests for tritium in ground water, tritium levels can relate to dates of precipitation, and therefore used to estimate when the water was recharged (the age of the water). This works for water that entered the ground after 1953.

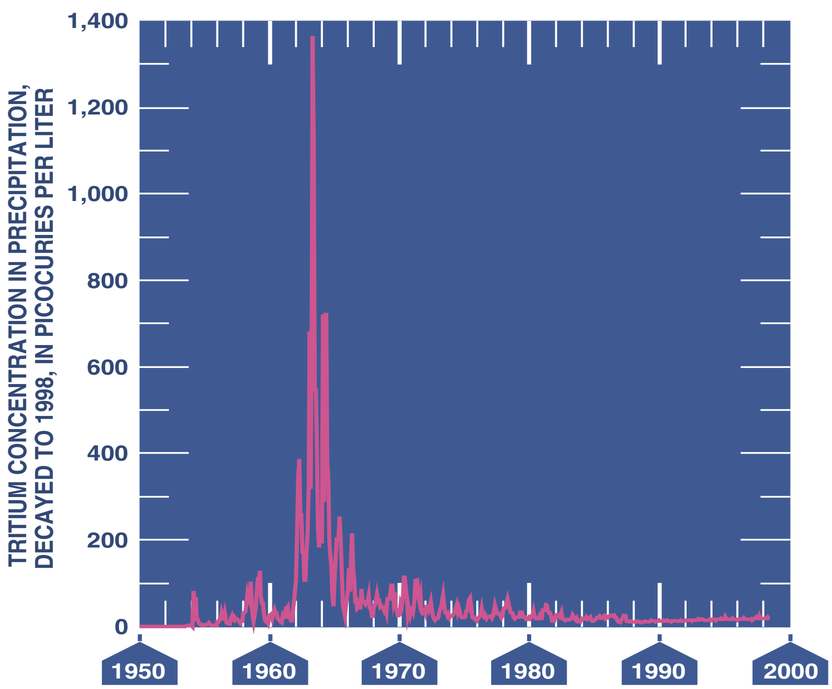
Because tritium is radioactive, its concentration is constantly changing and decreases in concentration by half every 12.4 years (this is known as the radioactive half-life for tritium). Above-ground nuclear weapons testing ceased decades ago and tritium levels are now approaching natural background levels, so scientists will not be able to use tritium alone to age date water for much longer.

Another important isotope is carbon-14. Carbon-14 occurs naturally in carbon dioxide. The carbon-14 in the atmosphere is taken up by plants and animals, as well as deposited in some rocks as they form. Once the carbon-14 is isolated from the atmosphere, it begins to decay into carbon-12 (the typical atom of carbon). The half-life of carbon-14 is 5,570 years. Therefore, by looking at the ratio of carbon-14 to carbon-12 in a buried plant or animal remains, the date of death can be estimated, or in rocks, the date of formation. This is a common practice for dating wood and animal remains from the last ice age.

This also works for water. When ground water is recharged, it contains levels of carbon dioxide. By looking at the ratio of carbon-14 to the resultant carbon-12, the age of the recharge can be estimated. Ground water has been dated using carbon-14 to dates from 50,000 to 80,000 years before present. This kind of information is important in determining how long ago water was recharged into an aquifer and the rate of flow within an aquifer.

Other types of radio-active isotopes are used by hydrologists. Chlorine-36 has a half-life of 300,000 years, so it can be used to date very old water. Tritium and iodine-129, as well as other isotopes, are used to identify and track contamination of ground water by nuclear waste.

Therefore, because the rate of decay in radioactive isotopes is known, it can be used as a tool to age-date ground water. However, this provides only part of the story. In addition to determining ages, aquifer tests, models, and other tools are needed for obtaining an overall conceptual picture of the hydrology for a region. Stable and radioactive isotopes provide an important part of this process.



Source: Cordy, G.E., Gellenbeck, D.J., Gebler, J.B., Anning, D.W., Coes, A.L., Edmonds, R.J., Rees, J.A.H., and Sanger, H.W., 2000, Water quality in the central Arizona basins, Arizona, 1995–98: U.S. Geological Survey Circular 1213, 38 p., online at <http://pubs.water.usgs.gov/circ1213/>.

Chapter 25

Water Use

How people use water really depends on where they live. In many parts of the world, societies are not strongly industrialized and most water use goes towards human consumption and crop irrigation. In the U.S., the largest water withdrawals were for thermoelectric power generation and irrigation. A USGS report on water use in the U.S. describes that 408 billion gallons of water per day were used in the U.S. in 2000 (Hutson and others, 2004). Of this total amount of water, about 195 billion gallons per day were used for thermoelectric power. But, much of this was saline surface water and represents water used for once-through cooling at power plants. About 52 percent of fresh surface-water withdrawals and about 96 percent of saline-water withdrawals went towards thermoelectric power generation. One could argue that because saline water is not available for other uses, such as drinking or irrigation, without expensive treatment, it should not be counted when considering how water is used in the U.S.

With that thought in mind, let's look at how freshwater was used in 2000. Irrigation accounts for most freshwater use, at about 137 billion gallons per day in the U.S. in 2000, or about 40 percent of all freshwater withdrawn. California used the most irrigation water, about 30.5 billion gallons per day, or about one-quarter of the total irrigation withdrawals for the country. The next biggest user of irrigation water is Idaho at about 17 billion gallons per day in 2000. Nevada only used about 2 billion gallons per day in 2000. Public water supplies (water for communities) were the second biggest use of freshwater in the U.S., with about 43 billion gallons per day used in 2000. The big users were California, Texas, Florida, and New York where large populations live in urban areas. For comparison, California used about 6.1 billion gallons per day in 2000 for public water supply, whereas Nevada used about 629 million gallons per day for the same period (Hutson and others, 2004).

Other water use categories are industrial, mining, domestic, livestock, and aquaculture. Of these, industrial was the largest at about 5 percent of all water use for the U.S. in 2000. Mining accounted for less than 1 percent of all water use. If you look at the water use report cited above, it does not list Nevada in the category of water use for mining. This is because water pumped for dewatering mines, which can be huge quantities in areas such as in northern Eureka County, are not heavily used for processing ores. Much of this water pumped from the ground either was applied as irrigation (and accounted for in this category) or put into streams. So the water was not actually used for mining, but rather was transported from one place to another. Domestic water use was less than 1 percent of the total water use for the U.S. and included water used inside and outside of homes that is supplied from private sources (nonpublic water supplies). Uses included washing dishes, bathing, flushing toilets, consumption, and watering lawns. The biggest users of domestic water are California, Michigan, and Florida. Livestock and aquaculture (farm-raised finfish and shellfish) both account for less than 1 percent of total water use for the country (Hutson and others, 2004).

It is interesting to look at water use in terms of surface water and ground water. Surface water is used more than ground water for thermoelectric power, public water supplies, irrigation, industrial, and aquaculture. Ground water is used more than surface water for domestic supplies, livestock, and mining. If one considers only freshwater and ignores saline-water withdrawals, 40 percent of the total water used was for irrigation and of this, about 58 percent of the water came from surface-water sources. About 63 percent of public water supplies come from surface water (cities rely heavily on lakes, streams, and reservoirs for their water). In stark contrast, about 98 percent of domestic water supplies come from ground water (Hutson and others, 2004).

So how does Nevada use its water? According to Hutson and others (2004), in 2000, Nevada used about 2.8 billion gallons of water per day. Of this amount, about 2.1 billion gallons per day were used for irrigation, or about 75 percent of total water use. Sounds like a lot of water, but Nevada ranks 16th in the nation for water use for irrigation, so by comparison, this number is not so surprising. This makes even more sense when considering that Nevada only receives about 9 inches of precipitation per year for much of the State, and that irrigation is essential for most vegetation to survive in this environment. About 629 million gallons per day go to public water supply, or about 22.4 percent of the annual water use. Thermoelectric power accounted for 36.7 million gallons per day, or about 1.3 percent. Other categories, such as domestic and industrial, were less than 1 percent of total water used in Nevada for 2000.

As one would imagine, when looking at public supply for water use in Nevada, the larger urban areas are the big users. Preliminary estimates for Nevada counties in 2002 show that Clark County uses about 73 percent of the total public supply and Washoe County uses about 14.5 percent. Together these two counties account for about 87.5 percent of the public supply water use for the entire state. The next biggest users are Carson City, about 2.7 percent, Elko County, about 1.8 percent, and Douglas County, about 1.6 percent. The rest of the 12 counties in Nevada combined make up about 6 percent of the total annual water supply use (Hutson and others, 2004). Of course, this is entirely reasonable when one looks at the population distribution for Nevada and the fact that most rural users are on domestic water supplies. Keep in mind that these numbers are just estimates, but they do provide a good representation of how public water is used in Nevada.

How an individual house uses water really depends on many factors, such as how many people occupy the home (in my case, how many kids you have and how long do they spend in the shower each day), the size of your lot, and where you live (desert verses the wet Northeast U.S.). SNWA has a web site that shows total residential water use in the Las Vegas area (Southern Nevada Water Authority, 2005). According to this web site, residential use accounts for 59 percent of southern Nevada's drinking water use, and residents use about 70 percent of their drinking water outdoors (90 percent in the summer). The breakdown is given as 47 percent of the water goes to effective landscape outdoor use, 23 percent as wasted landscape water, 8 percent for toilets, 6 percent for laundry, 5 percent for showers, 5 percent for faucets, 4 percent for leaks, and 2 percent for baths, dishwashers, and other uses. SNWA points out that between 20 to 30 percent of residential water is lost to leaks and waste water. These figures probably can be applied for much of Nevada, not just Las Vegas, and it shows not only how to avoid wasting water, but also the importance to Nevadans to have lawns, trees, and gardens. SNWA has been making a strong effort to educate the public and to help residents conserve this valuable resource.

Chapter 26

Water Sustainability

In October 2004, a workshop on water sustainability was held at the University of Nevada at Las Vegas. The focus of the workshop was to address the issues of present and future water demands for southern Nevada. In this chapter, the main points of discussion at the workshop will be summarized. Please note that these are points raised and do not express any opinions or interpretations of my own.

The major topics of the workshop dealt with drought, water supplies from the Colorado River, population growth in southern Nevada, conservation, resource management such as banking surplus water, and In-State resources.

The drought, which at the time of this writing is in its fifth year, affects much of the Western U.S. and has caused major stress on hydrologic resources. Declines in precipitation in the Upper Colorado River Basin (Colorado, Wyoming, Utah, and New Mexico) have lowered reservoirs and resulted in reduced flow in the Colorado River. These reduced flows have contributed to a significant decline in Lake Mead, the main source of water for Las Vegas and the Lower Colorado River Basin (Arizona, Nevada, and California). Although this current drought may be the most severe for any five-year period of historical record, tree-ring studies of past climates, before historical data collection, indicate that longer and more intense droughts occurred in the southwest. No one is certain when this present drought will end.

A major issue of discussion was on how different states are dealing with the current drought. The Upper Basin has been under restrictions, yet there are places in the Lower Basin that are perceived to be doing "business as usual." Much of the reason for this is that water deliveries to Lake Mead are controlled, in part, by the elevation of the lake. If the lake elevation is high enough, supplies can continue to be delivered, even during a drought. For example, 2002 was the driest year on record, yet levels in Lake Mead were high enough to allow for delivery of interim surplus water to southern Nevada; that is, water deliveries above Nevada's annual allocation of 300,000 acre-feet. Water levels in Lake Mead have remained high enough, to date, for interim surplus deliveries because of the huge amount of available storage. The large amount of storage in the lake acts as a buffer to declining lake elevations.

Water supplies in the Colorado River are managed by negotiated agreements between the seven States. SNWA uses levels in Lake Mead to define drought conditions, along with a relation of demand coupled with supply. The present pact governing the use of water from the Colorado River has some flexibility, but probably could not be renegotiated in the future unless all seven States saw some benefit. Nevada has been innovative in developing water-banking agreements with Arizona and California to store water during surplus years and help meet future demands.

Population growth in southern Nevada was another major topic of discussion. In the arid southwest, the availability of an adequate water supply may be the primary limiting factor on population size. For southern Nevada, growth is not only tied to water, but also to economic stability. Land development (construction) is the second largest industry in Las Vegas, and limits to this industry would have significant economic impacts to the community. The quality of life enjoyed in Las Vegas is supported, in part, through taxes and the economic benefits generated by the development industry.

Growth in southern Nevada is the highest in the country, at a rate of about 5 percent per year. Future limits to this growth may be associated with available water resources, increased energy costs, declines in quality of life as perceived by potential residents, and the physical limitations of Las Vegas Valley. At the present rate of growth, predictions indicate that land currently available for development in Las Vegas Valley will be built-out in the next 5 to 7 years.

Representatives from the building industry suggested that a main focus of water sustainability should be on conservation and education. Efficient home construction, wise land-use planning, reduction in potential waste of water, and community planning all can reduce costs, stresses on the natural resources, and help maintain the quality of life for residents. Adequate community education and design can significantly reduce water consumption.

Conservation has been a part of the solution for meeting water demands in southern Nevada. The largest use of Colorado River water in southern Nevada is for residential needs. About 70 percent of residential water use is for outdoor applications. Efforts have been made to conserve water by reducing turf through landscape conversion incentives and water-waste penalties. Another conservation practice is the use of reclaimed water (treated wastewater) for outdoor use. According to one panelist, all golf courses in Las Vegas, except for six at this time, have either converted or currently are converting to reclaimed water for irrigating fairways.

Resource management involves meeting present, and planning future, water demands using available supplies. Water banking is an important tool for resource managers because it allows for storage of water during years of surplus that can be used later when either supplies decrease or demand increases. Southern Nevada has been using water banking (which is really a credit system rather than the actual transportation of water) to meet future needs. Under water banking, Nevada allows either Arizona or California to use a portion of Nevada's yearly water right in water-storage projects, and then can withdraw an equivalent amount on demand in future years. Currently, southern Nevada has banked about 117,000 acre-feet of water in Arizona, 10,000 acre-feet of water in California, and another 250,000 acre-feet of water in aquifers in the Las Vegas Valley.

Another aspect of resource management is looking at In-State resources, such as the transfer of water from the Muddy River and Virgin River, and ground water from Clark, Lincoln, and White Pine Counties. It was pointed out that southern Nevada is looking at many options and presently plans to supplement water supplies through the importation of ground water from within and outside of Clark County. Decisions on implementing these plans are still under consideration. It also was pointed out that more research needs to be completed to understand the potential impacts of pumpage on the ground-water system in eastern Nevada.

In summary, the workshop mainly focused on the water supply from the Colorado River and Lake Mead and water use in Las Vegas. Lake Mead provides a huge source of water, but it is uncertain how climatic changes, such as drought, and increased demands related to growth will impact the reservoir's ability to continue to be a sustainable supply of water to Las Vegas. Efforts in resource management, such as conservation, water-efficient homes and landscaping, and water banking have helped alleviate some of the stresses on the water supply, but other sources of water to augment these supplies are required if growth in southern Nevada continues at the present rate. How these resources will be developed and managed to sustain predicted growth are key issues that need to be discussed now and into the future.

Chapter 27

Dowsing or Water Witching

Dowsing, or water witching, refers to searching for ground water using divining rods or other such tools. This practice has been around for centuries and many people firmly believe in its validity. Most ground-water hydrologists and other scientists completely dismiss it as a hoax and a scam. It is worth exploring both the facts and fiction associated with dowsing.

The practice of dowsing usually involves the use of divining rods, which typically are two wooden sticks or metal rods bent in some fashion and held in close proximity to one another. Dowsers also are known to use pendulums for locating buried objects and ground water. The idea is that the diving rods or pendulum will be charged with static electricity from the user's body, and when an object of high electrical conductance is crossed, the rods or pendulum will react by pulling downward, crisscrossing each other, or in the case of the pendulum, begin rotating in a circular path.

Different dowsers believe certain objects work better than others, and this seems to depend on the individual. Some prefer wires, others like rods or pipes, some use only willow or other wooden instruments, and some like the pendulum method. Not everybody seems to have the ability to be a dowser, whether it's because of different electrostatic energy in some people or because some are more sensitive to these signals.

So, does it actually work? That is a matter of opinion and, to a certain degree, faith. Strong evidence exists that humans can detect changes in an electromagnetic field. The human body generates electric pulses (our nervous system) and we seem to be cognizant of changes in electric current around us. We have all observed the ability for a person to generate static electricity (just walk across a carpeted floor in your socks and touch something metal to experience this). But how this energy and sensitivity can be harnessed to detect ground water may be a difficult bridge to cross.

Most ground water occurs in pore spaces in between sediments or in rock openings (see previous discussions on porosity and ground water). The top of an aquifer or the water table generally is a relatively flat, broad surface. To walk across a field and say that one place is better for finding water than another is unrealistic when the water underlies an entire area. The issue here is not so much where to drill, but rather how deep.

Many people have this idea of underground rivers and lakes. This really is not a valid concept except for areas of karst (caves), and even then, not very common. Maybe some of the misconception comes from the reference to ground-water reservoirs, which really refer to aquifers (and again, these are usually saturated sediments and rocks). So, if someone feels they can tap into an underground river, in most cases they are quite mistaken.

However, ground water does tend to occur in fractures in bedrock. Sometimes, if the bedrock is very tight, such as a granite or basalt, unless you drill into fractures, you probably won't get much water, if any. However, the fractures can provide variable amounts of water to wells that intersect the fractures. This might be where people get the idea of underground rivers, because wells that do not intersect fractures might be dry, whereas other wells adjacent to these dry wells might intersect fractures and produce water. People sometimes envision this as "hitting an underground river."

The question is whether dowsers can detect fractures or karst at depth. Various studies have demonstrated that some dowsers (this refers to "some" because like any profession, there are individuals that are successful and some that are not) can detect buried pipelines, septic tanks, cables, and other such shallow objects. Some people would argue that this is because of the electromagnetic energy (conductivity) of the buried objects being felt by the dowser. Others would argue that any buried object lies below a surface that has been disturbed in the past (when the object was buried) and the dowser is just sensitive to small undulations or changes in the land surface above the object. It is difficult to say for certain which accounts for the documented successes, but maybe it depends on the dowser.

Deeper variations in the geology, such as fractures or karst occurring hundreds of feet (or more) below the surface is a different story. Most scientific equipment with very sensitive capabilities have difficulty identifying fractures and small amounts of karst at depth, and this becomes more difficult with increasing depths. Scientists use techniques such as seismic reflection and ground-penetrating radar to search for such features. The accuracy (and success for identifying smaller features) is limited and usually depends on the energy source applied (such as seismic waves or radar). These energy sources are much larger than the static electricity produced by a human body. Arguably, the capability for these sensitive instruments to detect and identify variations in the subsurface exceeds the capabilities of human senses. Many people feel that human senses actually are keener than we have measured and that there may be many aspects of the human mind and perceptions that we do not understand. Whether this transfers to an ability to detect variations in deep subsurface remains debatable.

In summary, the validity of dowsing depends on the viewpoint of the individual. As pointed out, some evidence supports dowsing in shallow conditions, but it is highly questionable as to the accuracy for deeper features. In most places, ground water occurs as a planar surface and it makes no difference if one drills in one location verses 100 feet away. In the case of fractures and karst, most precise scientific instruments have difficulty identifying specific features at great depths, so it is questionable how much better human senses might be in locating these conditions. So, most scientists do not believe dowsing is valid. But, there is much scientists don't understand about the world and about the human body, so to discount dowsing entirely at this point would be premature and additional research would help answer many questions. What one believes is a personal choice and a matter of faith in one system or the other.

Chapter 28

Your Questions Answered

Author's Note: I want to address a few of the many questions I have received. I think these questions have a general interest, so I wanted to share them and my answers with you.

Question 1: I have a question about the area of ELY – it's water? Since the west is going through terrible drought, would that town be worse off?

Response: Many places in the west are experiencing the effects of the drought. It is probably most felt on surface water, where lower amounts of precipitation have caused decreased streamflow (Lake Mead and Lake Powell are dropping in stage because less water is coming in). We tend to see drought effects quickly in surface water because it is more reactive to climate conditions (same reason we get flash floods during heavy precipitation). The drought is affecting ground water and we do see a decrease in ground-water levels in many places, but the impact is less visible than in surface water because most aquifers are huge reservoirs of water and it takes time to show large changes. Most of rural Nevada uses ground water, and therefore, the drought, although important, has less immediate impact than it might on larger cities that use surface water. Natural events, like drought and wet periods, usually have limited extent (a few years to decades) which will allow ground-water levels to rise and fall dependent on the climatic conditions. I think you need to look at long term records (water levels over many decades) to get a good handle on what the water conditions will be over the long run. Typically, natural changes in ground-water levels related to climate are much less than human-induced changes due to pumping.

Question 2: It appears to me, eyeballing popular maps and driving the Sunnyside cutoff, that the White River flows to the south to the Pahranagat Lakes--and that those lakes, when full, empty into the Muddy/Virgin/Lake Mead water bodies. If so, that would make the White River Valley part of the Colorado River drainage, not part of the hydrologic Great Basin. Can you confirm whether that is the case? I would guess that in all the Colorado River litigation someone has made a determination about that, even if the White River does not materially contribute to the Las Vegas / Imperial Valley water supply. (If the Pahranagat Lakes don't drain, what keeps them fresh?)

Response: The area we refer to as the Great Basin was originally defined by Fremont (1845). "The intermediate region between the Rocky mountains and the next range [the Sierra Nevada] containing lakes, with their own system of rivers and creeks, (of which the Great Salt Lake is the principal), and which have no connexion with the ocean, or the great rivers which flow into it" (Fremont, 1845). In this classic definition, the Great Basin encompasses most of Nevada, western Utah, and parts of California, Oregon, Idaho, and Wyoming.

You are correct in that the White River flows to Pahranagat Lakes and that in the past, surface runoff continued south to the Muddy River and the Colorado River. Most delineations of the Great Basin (hydrographic, physiographic, and floristic), however, include the White River in the Great Basin. The hydrographic or classic definition of Fremont includes the White River because Pahranagat Lakes have not had surface discharge to the Muddy River in historic times. This definition is similar to the Great Salt Lake that once was connected to the Snake River during a past high stand. In contrast, Meadow Valley Wash (east of the Pahranagat Lakes), and Muddy River Springs and Las Vegas Valley (south of Pahranagat Lakes) are often excluded from the delineation of the Great Basin in the classic definition because surface runoff has historically reached the Colorado River. For a detailed history and delineation of the Great Basin, I suggest you read Grayson (1993).

Other delineations of the Great Basin region consider ground-water flow. The ground-water flow system in the White River drainage is similar to surface runoff in that it also flows to the south. However, unlike surface runoff, ground water presently is flowing into the Colorado River drainage. The contributing area for the ground water that flows into the Colorado River drainage, as estimated from ground-water budgets, ground-water levels, and chemistry, is thought to extend as far north as Butte Valley, northwest of Ely, although ground water may take centuries to millennia to travel from the northern end to the Colorado River drainage. This ground-water flow system known as the White River flow system is a series of basins made up of carbonate rock that extend from within White Pine County down to the area around Muddy Springs. In the White River flow system, many springs (such as Muddy Springs, Ash Spring, and Crystal Spring) are fed by discharge from the carbonate aquifer (as shown from geochemical analysis). Some delineations of the Great Basin include Meadow Valley Wash, the Muddy Springs region, and Las Vegas Valley because ground-water flow connects these areas with areas within the Great Basin.

Other delineations exclude all basins that contribute either surface runoff or ground-water flow to the Colorado River drainage (including those that contribute ground-water flow to the White River flow system) even though surface drainage in several of the basins has no outlet to the ocean. If one accepts the classic definition of Fremont (1845), then the White River should be within the Great Basin; however, if one also considers ground-water flow as part of the delineation, then the White River flow system could be excluded from the delineation. The difficulty in excluding the White River flow system from adjacent areas in the Great Basin is that the boundary of the White River flow system is not known exactly (the area does not need to follow topographic divides) and the boundary could change as a result of ground-water pumping either within the White River flow system or in adjacent areas.

In response to your last question as to why the Pahranagat Lakes contain freshwater, the most likely answer is that ground water moves water into and out of the lake in a manner similar to the Ruby Marshes (Lakes) in Ruby Valley. As in the Ruby Marshes, inflow to the lakes is a dominant feature, and therefore a large supply of freshwater coming into the lakes limits the salinity concentrations. Flow from Ash and Crystal Springs supply water to the Pahranagat Lakes. However, these lakes probably also receive ground-water inflow from the surrounding mountains. I'm not an expert on the local hydrogeology of these valleys but I assume that Pahranagat Lakes are flow-through lakes, which means that the lakes both have input and output to the underlying aquifers, and as such serve as a window to the aquifers. During periods of high lake levels (during the past glacial period), there can be spillover to surface runoff from Pahranagat Lakes to the south. **Much of this response was with the assistance of Dave Prudic, U.S. Geological Survey.**

Question 3: In the chapter on precipitation and its enclosed map, by my estimate, it seemed that Elko had more water than Ely. Am I correct? Which towns/cities have the most precipitation?

Response: The map that shows precipitation distribution indicates that most precipitation falls in very high elevations. In the Ely area, that would be around Great Basin National Park on some of the higher peaks. In the Elko area, that would be in the Ruby Mountains and other high peaks. If you look at the precipitation record for the city of Ely (period of record 1897–2003) it gives an average annual precipitation of 9.53 inches. The record for Elko (at the airport, period of record 1890–2003) also is an annual average of 9.53 inches. So, the two cities have virtually the same precipitation amounts over the long period of record. See the interactive web page at http://www.wrcc.dri.edu/summary/mapnv.html and click on any area for which you want to see weather records.

Please keep in mind that once the precipitation falls in the mountains, where it ends up as streamflow and ground water greatly depends on numerous variables. It is hard to make any conclusions about which town has more water based on just a precipitation distribution map.

Question 4: The question is related to cooking foods, and especially adjusting cooking temperatures at high altitudes. Specifically, when adjusting a cooking thermometer to freezing (32° F sea level) and boiling (212° F at sea level), are there adjustments for high altitudes?

Response: Let me take off my USGS ball cap and put on my Julia Child chef hat. I did some simple calculations for the elevation at Ely (6260 feet at the airport) and found that for that altitude, water boils at around 200° F (verses 212° F for sea level). This can be a problem because it often takes longer to cook foods according to the instructions because boiling is reached at lower temperatures.

When I worked in the Andes of Peru back in the 1980s, we had a base camp at 17,000 feet. We used pressure cookers to cook our food because at that high altitude, water boiled at lower temperatures and food didn't cook properly. The pressure cookers increased the pressure in the cooking vessel and therefore allowed higher temperatures to be reached before boiling occurred.

There are stories of Tibetan monks who usually drank their tea when the cup of water was boiling because at their high altitude, this was a lower temperature. When these monks went to visit other places closer to sea level, they would burn their mouths trying to drink the tea at that boiling point, which was much hotter.

The freezing point for water at Ely's altitude is about the same as at sea level. Therefore, one could use a bucket of slushy ice water and be at the normal temperatures for calibrating a cooking thermometer.

Pressure does play a part in changing freezing points, which is often illustrated using the ice skate example. In this example, the pressure at the edge of the skate blade on the ice, along with friction and other factors, actually causes melting to occur at that point and therefore allows glide.

Likewise in temperate climates, many glaciers, which are masses of ice, are actually wet at their bases because of the pressure melting caused by the weight of the overlying ice mass. Water at the base of some of these glaciers has been credited with causing surging or relatively rapid movement of the glacier.

In the two examples given, other factors affect the melting, but these are kept simple to illustrate the point. Also, these two conditions described are much more extreme pressure differences than that caused by altitude in Ely.

Question 5: Does White Pine County have that much water to share with the Southern Nevada Water Authority?

Response: That is a really important question and there is not a simple answer. What quantity is enough to provide for the exportation of water and preservation of the resource? That really is a societal decision, not just a science issue. The input of a wide variety of groups, such as the general public, White Pine County residents and water managers, SNWA, the State, Department of the Interior agencies (BLM, NPS, and USFWS), legal authorities, environmental groups, and various other groups all need to be considered in determining beneficial use and adequate protection of the resource.

As hydrologists, we can estimate how much water is available in an aquifer and how pumping will affect water levels in an aquifer, but to determine what amount of withdrawal is enough and what potential effects are acceptable are decisions for society, and especially of interest to the people and water managers in White Pine County.

In White Pine County, a large carbonate aquifer system exists that is many thousands of feet thick in places. This bedrock aquifer is overlain by unconsolidated alluvial sediments that form the aquifers used for most local needs (irrigation and domestic users). In the deep carbonate aquifer, there is a vast amount of water (studies need to be done to further quantify this amount, but present estimates show it to be quite large).

It is probable that large amounts of water can be pumped from this bedrock aquifer and any effects, such as declining water levels, might not be observed for many years or even longer. Initially, water withdrawn would come mainly from storage in the aquifer and not from present recharge. However, it is not known how much water can be pumped from the aquifer without creating significant water-level declines until aquifer tests are completed.

Aquifer tests (pumping the aquifer for sustained periods of time and measuring related declines in water levels) are needed to assess storage and permeability of the aquifer so that potential effects of pumping can be determined. SNWA has proposed an aquifer test at a MX missile well site in Lincoln County.

As a hydrologist, I would agree that aquifer tests are needed before we can make accurate estimates of the aquifer properties. But many people have asked what would happen to the water pumped during this long (maybe years) aquifer test? Some people have raised this question because, as they would argue, if the water is pumped south, either as water supply to Clark County or flow to Lake Mead, then there could become a dependence on the water and the test could become a permanent process. I don't know what the plans are at this time (if the aquifer test will occur and, if so, how the pumped water will ultimately be used during the test).

Also, what is the hydraulic connection between the deep bedrock aquifer and the shallow alluvial aquifers where most existing wells are located? Will pumping from the deep aquifer affect the shallow aquifers and potentially lower water levels and dry up present irrigation and domestic wells?

Conceptually, the alluvial and carbonate aquifers are connected in places, but the degree and location of connection are unknown for many basins. Deep wells that extend through the alluvium and into the bedrock are scarce, so our knowledge of the hydraulic connection is really limited. I feel there needs to be a better understanding of this connection before one can be certain that the impact is minimal. This also relates to concerns from the BLM about reducing the water table in the alluvial aquifers and affecting the habitat for sage grouse and other animals and plants.

An additional question being asked is: What affects pumping would have on the springs in the discharge zone? The bedrock aquifer is a large flow system and it discharges in a series of springs in eastern and southern Nevada, such as Muddy Springs. If the water is lowered in the aquifer, will the spring discharge decline, or the springs dry up? This is a question NPS and USFWS want answered because they are responsible for the wildlife, including threatened and endangered species that live in these springs. Conceptually, spring discharge could be reduced by pumping from the bedrock aquifer, but no one is entirely certain at this point by how much or at what point in time. Estimating potential impacts to spring discharge will depend, in part, on how the system is conceptualized. Hopefully, more data and more studies will allow for better understanding of the aquifer system.

Now, as for the question about what is acceptable to society when weighing the pros and cons of water exportation. In reality, it may be a very long time before any effects are noticeable in the aquifer. Along those lines, once changes are observed in such a huge system, it may be very difficult to reverse those changes (the response either way could be quite delayed).

As I've stated before, you can't stress a system without changing it. Potential effects include declining water levels in bedrock and alluvial aquifers, declining spring discharges, and reducing ground-water discharge to lakes and playas. In some cases, such as water lost to evaporation from playas, this might not be a concern to many people. Because so much of the water in the hydrologic cycle in the Great Basin is lost to ET, a reduction in this loss might be insignificant to many people, and maybe even unnoticeable. However, no one can predict the effects with complete certainty until the system is stressed (such as an aquifer test) and we actually observe the changes. Then, information from the aquifer test is put into a transient flow model for the aquifer system and responses to stresses are modeled.

Let's put the issue in a different perspective (a little less scientific). Suppose you had a huge bank account that you plan to use to ensure the stable future for you and your family. Now, probably there is enough money in your account for you to consider sharing with others who need some extra help or for investing for economic gain. But how much is enough and yet still secure your own future and protect your present way of life? Any additional spending from your account affects the balance, but how much is acceptable, or even noticeable, considering there are many inputs and outputs from your account?

Obviously, each of us would answer this differently and there is a huge spectrum of possible choices that could be offered. This is why water use and potential exportation is an issue for society and not strictly a science issue. Scientists can quantify how much is there, but how it is used and what is acceptable is a decision for society.

Wheeler Peak and Spring Valley from Highway 50. Photograph by M.L. Strobel, USGS.

Lake Tahoe, from the Gondola fire burn area. Photograph by K.K. Allander, USGS.

Chapter 29

Lake Tahoe

Lake Tahoe, which lies on the border between Nevada and California, has been described as a national treasure because of its beauty and clarity. Congress considered making the lake a National Park in the 1912, 1913, and 1918 sessions, but the effort was never successful. The Lake Tahoe Basin draws visitors from all over the world every year for its scenic beauty; outdoor activities such as skiing, hiking and boating; and its casino and entertainment industry.

Mark Twain (1872), in his book "Roughing It" described Lake Tahoe as "the fairest picture the whole earth affords." He went on to say that "three months of camp life on Lake Tahoe would restore an Egyptian mummy to his pristine vigor, and give him the appetite like an alligator. I do not mean the oldest and driest mummies, of course, but the fresher ones."

Geologically, the Lake Tahoe Basin is quite interesting and complex. To understand the entire geologic history, the formation of the Sierra Nevada would need to be discussed, which would take up a few book chapters in itself. Focusing specifically on Lake Tahoe, the present basin was originally formed a few million years ago when huge pressures along two major parallel faults caused the uplift of rock blocks to the east and west of present Lake Tahoe Basin. The uplifted blocks, composed mostly of granite, formed mountain ranges surrounding the present lake, whereas the dropped block between the two uplifted blocks created the valley now occupied by Lake Tahoe.

Following the creation of the valley, a river flowed between the two high ridges. The river flowed for millions of years before another geologic event changed things. Lava flows from the now-extinct volcano Mt. Pluto spread across the northeastern part of the valley and formed a natural dam. The valley filled with water and a natural lake was formed, spilling out at the present Truckee River at Tahoe City. During the Pleistocene (what we often refer to as the Ice Age), glaciers filled many of the valleys in the Lake Tahoe Basin and eroded large amounts of rock and creating U-shaped valleys. Many of the smaller lakes in the Lake Tahoe Basin were formed in depressions created by the glaciers or behind large ridges of glacial sediment called moraines.

The result of these geologic events is the present Lake Tahoe. Lake Tahoe is the second deepest lake in the U.S. (maximum depth is 1,645 feet), and the tenth deepest lake in the world. The lake is about 22 miles long (north to south) and about 12 miles wide, and has an average depth of 1,000 feet. The surface area of Lake Tahoe is 191 square miles and the average surface elevation is 6,225 feet above mean sea level (this fluctuates with seasonal and climatic changes in streamflow into and out of the lake and evaporation) (U.S. Geological Survey, 2004).

The Carson Range separates the Lake Tahoe Basin from Carson City and the Carson Valley. It is interesting to note that the bottom of Lake Tahoe is actually lower than the elevation of Carson City. For those who have driven from Carson City to Lake Tahoe, this is a good visualization of the depth of the lake.

So, how much water is in Lake Tahoe? According to the Lake Tahoe Data Clearinghouse (U.S. Geological Survey, 2004), the water contained in Lake Tahoe, if distributed over a land area the size of California, would cover the entire State with 14 inches of water. Another interesting fact provided on this web site is that the amount of water in Lake Tahoe is equivalent to what could supply every person in the U.S. with 50 gallons of water per day for 5 years.

Lake Tahoe is fed by 63 tributaries that flow into the lake from around the basin. Only one stream, the Truckee River, flows out of the lake. Although a number of communities dot the shoreline, the majority of the Lake Tahoe Basin is undeveloped and much of this land area is managed by the U.S. Forest Service.

The lake has an interesting history. The Washoe people spent summers along Lake Tahoe, hunting and fishing in the area for thousands of years. The first recorded sighting of Lake Tahoe by a non-Native American was during an expedition led by John C. Fremont in 1844. In the 1860s, with the development of mining in Virginia City, the growth of other cities like Carson City and Reno, and the building of the Transcontinental Railroad north of Lake Tahoe, demand for wood from the Lake Tahoe Basin grew. Much of the forested land in the basin was clear-cut in the 1870s and 1880s. As mining began to fade and Lake Tahoe was "discovered" by people in California and Nevada looking for a vacation spot, the forest industry began to be replaced by the tourist industry. And since the early 1900s, much of the forests have returned to the basin.

One of the first interbasin transfers of water in Nevada occurred because of the mining boom at Virginia City and Gold Hill. Water needed to supply these growing cities and their mining industry, as well as growth in Carson City, the State capitol, resulted in the creation of Marlette Lake, Hobart Reservoir, Spooner Lake, and a system of flumes and pipelines. Flumes entered a 4,000-foot tunnel through the Carson Range and into a pipeline that could deliver up to 10 million gallons per day to Virginia City (a complete history can be found at http://parks.nv.gov/ltbc.htm). This pipeline system still works today.

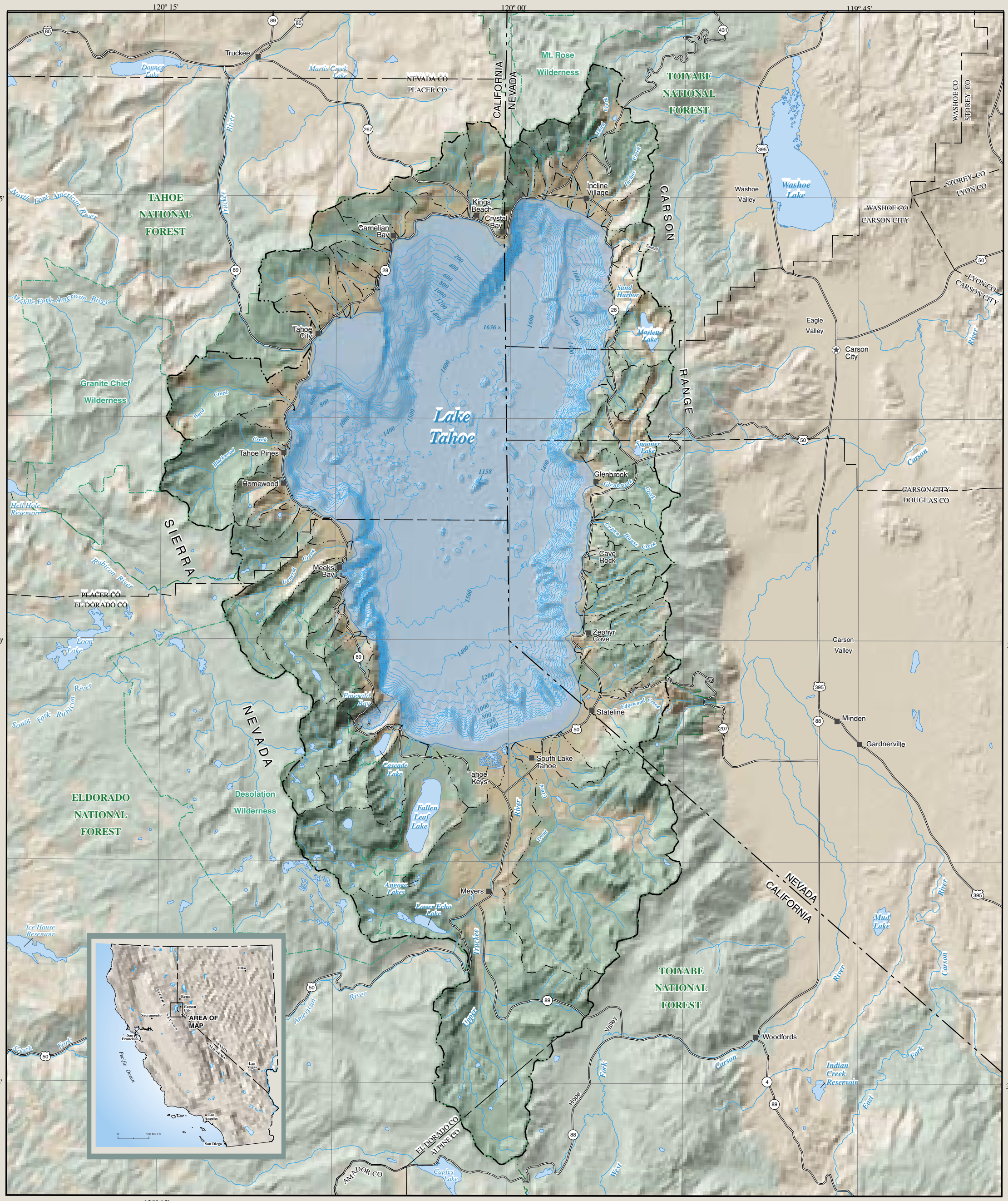
Some interesting facts about the Marlette Lake Water System: The project involved 21.47 miles of pipeline, 45.73 miles of flume, it used an inverted siphon consisting of a 12-inch diameter riveted iron pipeline to move water upgradient, and the pipeline was constructed over the roughest 7-mile section in just 6 weeks using only men and mules (American Society of Civil Engineers, 2005).

Besides being known for the incredible scenic beauty, Lake Tahoe also is famous for its clarity. The clarity is measured based on the Secchi depth, which is a measurement based on lowering an 8–10 inch white disc into the lake on a line. The deepest point of visual contact indicates the depth of clarity. The clarity of Lake Tahoe presently is about 60 feet deep (varies with season and location in the lake) and this clarity has declined at an average rate of about 1 foot per year for about the last 35 years. The reason for the loss of clarity has been attributed to increased algal growth related to increased nutrients in the lake and to increased suspended sediment related to stream transport of sediment to the lake. These and other issues of water quality are being addressed by numerous researchers working in the basin.

Lake Tahoe, often referred to as the "Jewel of the Sierras," certainly is one of the most beautiful places on Earth and a major attraction in Nevada. Hopefully, we will continue to enjoy its scenic beauty and clarity for many more generations.

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

WATER RESOURCES INVESTIGATIONS REPORT 99–4031
Smith, J.L., Stone, J.C., Rowe, T.G., and Gardner, J.V.
Selected hydrologic features of Lake Tahoe Basin
and surrounding area, California and Nevada, 1998



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000, 1969-85
Universal Transverse Mercator projection, Zone 10
Bathymetry data was acquired in August 1998 by U.S. Geological Survey in cooperation with University of New Brunswick. More information available *in* Gardner, J.V., Mayer, L.A., and Hughes Clarke, J.E., 1998, The bathymetry of Lake Tahoe, California–Nevada [online]: U.S. Geological Survey Open-File Report 98–509 (available on World Wide Web at <http://blt.wr.usgs.gov/tahoe/openfile.html> [last modified August 1998; cited October 1998])
Shaded relief for Lake Tahoe bottom areas shallower than 33 feet *from* National Oceanic and Atmospheric Administration, 1982, Lake Tahoe: National Oceanic and Atmospheric Administration map, 8th ed., scale 1:40,000
Forest areas from U.S. Forest Service digital data, 1996 and 1997
Wilderness areas from U.S. Forest Service digital data, 1997

MILES 5 0 5 10
KILOMETERS 5 0 5 10

For more information contact:
Public Information Assistant
U.S. Geological Survey
333 W. Nye Lane, Rm 203
Carson City, NV 89706
tel.: (702) 887-7649
fax: (702) 887-7629
email: usgsinfo_nv@usgs.gov
URL: http://nevada.usgs.gov

EXPLANATION

U.S. Forest Service land

- National forest
- Lake Tahoe Basin Management Unit

Other land—Darker shade is land within boundary of Tahoe Basin Management Unit

- **Boundary of national forest**
- **Boundary of wilderness area**
- **Boundary of Lake Tahoe Basin**
- **Boundary of subbasin**
- 800 **Bathymetric contour**—In feet below highest legal lake-surface altitude (6,229.1 feet above Bureau of Reclamation datum of 1929). Contour interval 100 feet

SELECTED HYDROLOGIC FEATURES OF LAKE TAHOE BASIN AND SURROUNDING AREA, CALIFORNIA AND NEVADA, 1998

By

J. LaRue Smith, J. Christopher Stone, Timothy G. Rowe, and James V. Gardner

1999

USGS
science for a changing world

Lake Mead from Space (Las Vegas is not in this image but is in the direction of the lower left corner of the photo).

Image by Jesse Allen, NASA, based on data provided by the Landsat 7 Science Team, available at http://earthobservatory.nasa.gov/Study/LakeMead/

Chapter 30

Lake Mead

Possibly the most important source of water to Nevada at the present time is Lake Mead. This is because Lake Mead serves the majority of Nevada's population and is critical to one of Nevada's major industries, tourism.

The area that is presently occupied by Lake Mead has a long and rich history. Man has been in the area along the Colorado River in southern Nevada for at least the last 11,000 years and possibly much longer. Archeological evidence of camps and settlements in the area date back many thousands of years. North of Las Vegas at Tule Springs, hearths, stone tools, mammoth bones, and other artifacts indicate the area was occupied by a people referred to as the Basketweavers (National Park Service, 2005). These people also occupied the Lost City along the Muddy River near the confluence with the Virgin River.

The first recorded non-Native American to visit the area was Jedediah Smith in 1826. In 1829, a new northern route for the Spanish Trail was established from the Muddy River through present-day Las Vegas (in Spanish, Las Vegas means the Meadows) and onto the Mohave River. Later, other explorers, including John C. Fremont and John Wesley Powell, visited the area. These were followed by a number of different Mormon settlements and various mining camps. Many of the sites of the early towns, such as Callville, Rioville, and St. Thomas, have been covered by Lake Mead (National Park Service, 2005), although recent declines in water levels in Lake Mead have exposed some sites.

Lake Mead formed following the completion of Boulder Dam (now called Hoover Dam). The lake is named for Dr. Elwood Mead, who was the commissioner for BOR from 1924 to 1936 and was the lead in designing the construction and completion of the dam. Boulder Dam was completed in 1935 and its completion created the largest artificial lake in the world at that time.

Lake Mead is one of many dams along the Colorado River. The two largest reservoirs on the Colorado River are Lake Mead and Lake Powell. Both serve as lifelines in a desert environment and both population and agricultural growth are dependent on these water bodies.

The water in the Colorado River is divided among various states that are part of the drainage basin to the river. The Colorado River Compact was established in 1922. This compact divided the river into the Upper Basin (consisting of Colorado, New Mexico, Utah, and Wyoming) and the Lower Basin (consisting of Arizona, California, and Nevada). Because the division was based on State boundaries and water basins do not follow these lines, Arizona, New Mexico and Utah actually drain into both the Upper and Lower Basins. The compact apportioned 7.5 million acre-feet of water per year to both the Upper and Lower Basins. In addition, the compact regulated the flow from the Upper Basin to the Lower Basin (established an aggregate flow of 75 million acre-feet of water over any consecutive 10-year period) and provided the right for an increase in the annual beneficial consumptive use of Lower Basin water by 1 million acre-feet (Southwest Hydrology, 2005).

In addition to the Colorado River Compact, the Boulder Canyon Project Act of 1928 authorized the construction of what would become Hoover Dam. The Act also apportioned the Lower Basin water such that Arizona received 2.8 million acre-feet per year, California received 4.4 million acre-feet per year, and Nevada received 300,000 acre-feet per year, or 4 percent of the 7.5 million acre-feet of water per year. In 1944, the U.S. entered into a treaty that guarantees Mexico 1.5 million acre-feet of water per year from the Colorado River (Southwest Hydrology, 2005).

At the time, 300,000 acre-feet of water per year for Nevada seemed adequate, given the population, limited irrigation, and small growth projections. Most of the water used in southern Nevada was ground water, which probably seemed limitless considering the needs and uses in the 1920s. However, significant changes in southern Nevada in the coming years increased the dependence on Colorado River water contained in Lake Mead.

In the early 1940s, industrial growth in southern Nevada related to the war efforts and the rise of the casino gambling industry began to boost the population numbers and the needs for additional water resources. As the demands for water increased, it was determined that ground-water supplies needed to be augmented with water from Lake Mead. Pipelines to bring Lake Mead water to the Las Vegas Valley were established, and dependency on that water supply grew. From the 1950s to today (2005), southern Nevada has seen a population boom and Las Vegas continues to be the fastest growing city in the country for most of the last decade. The needs for water to support the population growth in southern Nevada have now exceeded the allotment of water from Lake Mead as originally established in the Boulder Canyon Project Act.

One way that Nevada has been able to increase the amount of water it can withdraw from Lake Mead is to calculate the water withdrawals on consumptive use, which gives credits to return flow to the reservoir. What this means is that the 300,000 acre-feet per year is based on the overall balance of water removed from the lake. If, for example, 150,000 acre-feet per year of water is returned to the lake by means of treated wastewater, then that allows for 450,000 acre-feet per year to be withdrawn through the water intakes for supply to southern Nevada. In addition, water needs for southern Nevada are supplemented by use of ground water and by banking water during surplus years for use later. Presently, southern Nevada also is looking at other options to supplement the supply from Lake Mead, such as importing water from other basins in Nevada, banking unused portions of Nevada's Colorado River water in other States, and helping to develop desalination plants in California to augment their needs in exchange for water from Lake Mead (Southern Nevada Water Authority, 2005).

Hoover Dam.

In addition to the base allocation of water from the Colorado River, allotments fall under the designation of Interim Surplus. What this means is that based on the elevation of Lake Mead, additional water for domestic uses can be withdrawn. Therefore, if the lake is at 1,125 feet above sea level or less, only the 300,000 acre-feet of water can be withdrawn that year. At various levels above 1,125 feet above sea level, this is considered surplus water in the lake and additional water can be withdrawn (how much water can be withdrawn and how it is distributed is based on the specific elevations of the lake) (Southern Nevada Water Authority, 2005).

So, how much water is in Lake Mead? The lake varies in volume dependent on climatic changes. Recently, we have seen the lake dropping because of the prolonged drought in the Western U.S. and the volume has decreased significantly. Presently, the lake is down 90 feet from its level in 2000 and at the end of 2004, Lake Mead and Lake Powell were at less than 50 percent of their combined storage capacity (Southern Nevada Water Authority, 2005). According to the BOR, at its maximum size (the spillway gates at Hoover Dam are at 1,221.4 feet above sea level), Lake Mead contains about 28,537,000 acre-feet of water. At maximum, Lake Mead has a surface area of about 247 square miles or 157,000 acres, and extends for about 110 miles upstream along the Colorado River. The width can vary from a several hundred feet to about 8 miles depending on the canyons it occupies (U.S. Bureau of Reclamation, 2005).

In addition to being a source of water for the Southwestern U.S., Lake Mead also is a recreation destination for many boaters, swimmers, anglers, and other people who enjoy the outdoors. According to NPS, Lake Mead National Recreation Area covers 1.5 million acres, has 950 miles of shoreline, and attracts about 9.1 million visitors each year (National Park Service, 2001).

Hoover Dam itself draws almost a million people a year to its visitor center. U.S. 93, which is a major north-south route for commercial transport and visitor travel through Arizona and Nevada, crosses the top of Hoover Dam. Because of concerns of damage to the dam and water supplies resulting from potential vehicle accidents, the potential of vehicle-pedestrian accidents along the dam, and delays in traffic at checkpoints before crossing the dam, a new crossing is being constructed about 1,500 feet downstream of Hoover Dam. This crossing is known as the Hoover Dam Bypass Project and it is projected to be open to the public during 2008 (Hoover Dam Bypass Project, 2005).

Lake Mead continues to be a critical lifeline to populations and agriculture in the Southwestern U.S. and a source of water to sustain the majority of Nevada's population. As growth continues in southern Nevada, Lake Mead will continue to be important, even though other sources of water will need to be established to augment this need. Hoover Dam and the creation of Lake Mead show that man has the capability to tame nature to our benefit, but the recent drought has shown that nature can still call the shots. It will be interesting to see how Lake Mead and water distribution in general in the southwest will play a key role in population growth, agriculture, and politics in the coming years.

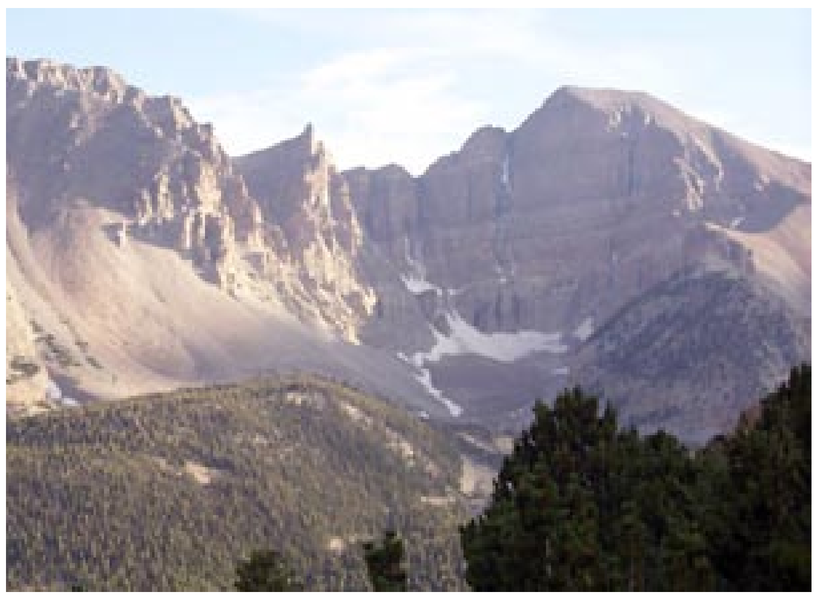
Lake Mead. Photograph by C.L. Westenburg, USGS.

Chapter 31

Great Basin National Park

Great Basin is Nevada's only National Park (except for a small section of Death Valley National Park in southern Nevada). It was established in 1986. Actually, the area of Lehman Caves was established as a National Monument in 1922 and much of the area that presently includes Great Basin National Park was protected as part of the Wheeler Peak Scenic Area of the Humboldt National Forest (http://www.great.basin.national-park.com/info.htm).

Water has been an important factor in the creation of many features at Great Basin National Park. Possibly the most prominent feature at the park is Lehman Caves. The spectacular features in the caves are a product of the interaction of water and geology. Many of the erosional and depositional features viewed around the park were created by glaciation, as ice scoured, transported and deposited rock material. Streams and springs in the Park provide habitat for various plants and animals, and have helped shape the topography of the area. Precipitation that occurs in the high elevations of the Park provides water to support pine and juniper forests and a variety of ground vegetation.



Great Basin National Park. Photograph by D.E. Prudic, USGS.

The first modern resident in the area to find and make public the existence of the cave was Absalom Lehman in about 1885. Ab Lehman opened up the cave to tourists and added wooden structures such as ladders to make the cave more accessible. Archeological evidence shows that Native Americans accessed the caves and used the caves as a burial place as early as 800 years ago. (http://www.great.basin.national-park.com/info.htm).

In order to discuss the hydrology of Lehman Caves, one must first discuss how caves are formed. Karst is the geologic term typically used to describe features such as caves, caverns, and solution pits, where rock material has been dissolved away to form these openings. Karst features typically form in limestone because this rock type dissolves readily when in contact with acids (and over time when in contact with slightly acidic water), but can also form in other rock types such as dolomite, salts (halite, gypsum, and others) and marble (which is metamorphized limestone).

Many field geologists carry a small bottle of dilute hydrochloric acid (HCl) with them for testing for limestone (calcium carbonate) in rock samples. When the HCl is put on limestone, there is a reaction where the solution bubbles and fizzes. It is a similar reaction when you place a drop of vinegar on some baking soda. The HCl reacts with the rock and lets off gases (bubbles) and dissolves some of the rock surface.

This same type of reaction happens naturally when water on the land surface percolates down into limestone rocks. The surface water contains dissolved carbon dioxide from the atmosphere and from the soils. This dissolved carbon dioxide makes the water slightly acidic (carbonic acid). The water then percolates down to the water table where it can dissolve the limestone bedrock over many thousands or millions of years (in geologic time, this is a rapid occurrence, but in human time, karst formation can be a very slow process, depending on the acidity of the water and the rock type). As the bedrock dissolves, caves are formed.

For a very good description and a more in-depth discussion of cave forming processes, please look at the Great Basin Nation Park web site at http://www.great.basin.national-park.com/hike.htm.

If Lehman Caves are in the range of hundreds of thousands to millions of years old, this implies that the water table relative to this location was much higher in the geologic past because much of the cave is dry. This change in the water level could be the result of various processes, such as climate change (during the Pleistocene, or Ice Age, ending about 8,000 to 10,000 years ago, many of the basins in Nevada were covered by large lakes), uplift of the mountains, or erosion by mountain streams causing a decline in groundwater levels. Whatever the cause, the drop in the water table resulted in Lehman Caves being mainly dry and accessible for walking tours.

Lehman Caves has an extensive concentration of speleothems (cave formations or decorations) which form from the deposition of calcium carbonate (limestone) carried by water dripping and splashing into the cave. Speleothems in Lehman Cave include stalactites (elongated features hanging from the ceiling), stalagmites (elongated features rising up from the floor), columns (typically connected stalactites and stalagmites), soda straws, draperies, including a feature known as cave bacon, flowstones, cave popcorn, and shields. Shields are fascinating features that look like two disks or circular plates cemented together. Lehman Cave has over 300 shields and is known for these features (http://www.nps.gov/grba/lehmancaves.htm).

Glaciation at Great Basin National Park has had a dominant effect on shaping the area's topography. Glaciers are masses of ice and snow that remain from year to year and move downslope because of gravity. In the past, many glaciers covered parts of Great Basin National Park, and today the park has Nevada's only glacier.

Speleothems in Lehman Caves.

Glaciers can shape the topography by both erosion and deposition. Often, glaciers will scour out bowls (referred to as cirques) which may later fill with water and become mountain lakes. Glaciers can erode out U-shaped valleys and can transport much sediment down the mountains. Likewise, glaciers can alter the topography by depositing huge hills and ridges of sediment known as moraines. Many of the long ridges and hills in the park are moraines resulting from glacial deposition.

Water action by precipitation and runoff also has shaped much of the present topography of the park. Erosion from rainfall and snowmelt has weathered and transported sediment downslope from the mountains. Water that gets into cracks and openings in the rock and then freezes (and expands) can cause rocks to break apart. Streams can erode into the land surface and can transport and deposit sediment along their paths. All of these processes have had an impact on shaping the face of Great Basin National Park.

The USGS, in cooperation with the NPS, has completed a study of the susceptibility of water resources in Great Basin National Park. The purpose of the study was to determine areas within Great Basin National Park where the water resources (springs and streams) could be affected by ground-water withdrawals from the adjacent valleys. In addition, the study quantified the discharge of major streams and springs within the Park, assessed the natural variability of their flow.

As part of this study, eleven stream gages were installed to monitor discharge of springs and streams for a two-year period. The gains and losses in streamflow were correlated to the geology along six streams to determine areas susceptible to ground-water withdrawals in adjacent basins.

The report of the study results has been prepared and, at the time of this book, is in internal review with the USGS. Once available, the report can be accessed electronically through the USGS web site at <http://nevada.usgs.gov>.

Great Basin National Park has been greatly shaped and influenced by various water processes. In addition to natural conditions and variations, human impacts also may affect the hydrology of the Park. The Park is a good example of the importance of water in shaping the geologic features, topography, and future changes in Nevada.

USGS hydrologists, Peggy Elliott and Dave Beck, measuring discharge at Great Basin National Park.

Chapter 32

Wetlands

Wetlands have been an issue of controversy for many years. Hydrologists see these features as important areas of ground-water recharge and discharge. Biologists understand that wetlands are important to a wide range of flora and fauna, and that wetlands have their own complex environments. Some developers see wetlands as legal barriers to new constructions, whereas others see the aesthetic value to property. Some farmers see wetlands on their property as land that could be drained and cultivated. Some ranchers see the value of wetlands as watering holes for livestock. Environmental protection agencies often view wetlands as important filters of pollutants and sediments from streams.

So, the big question is "What is a wetland?" Various definitions are available for wetlands and each have a basis in science and legal terms. Possibly the most widely accepted definition for wetlands is one that has been accepted by the USACE and the USEPA

They define wetlands as *"Those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas"* (Federal Register, 1982; Federal Register, 1980).

Wetlands are protected as part of the Clean Water Act, Section 404, and therefore, accurate delineation of wetlands is important so that these features are not damaged by human activities. Wetland delineation is a whole science in itself and it takes special training to be able to identify what are wetlands and where the boundaries of the wetlands extend. And what works in one state or region may not be applicable to different environments (Minnesota wetlands are very different from wetlands in Nevada, Florida, or Alaska and each region is unique).

Wetlands are defined by three characteristics: vegetation, soil, and hydrology. In general, some aspect from all three of these characteristics must be met to be defined as a wetland, but exceptions can be based on abnormal conditions such as prolonged drought.

Wetland vegetation consists of hydrophytic plant life that occurs in areas of permanently or periodically saturated soils. The saturation of the soils needs to have sufficient frequency and duration to be a controlling influence over the types of plants that will exist in these soils. Most wetland vegetation found in the U.S. has been classified and in most cases scientists can readily identify whether the vegetation qualifies as wetland or upland plants.

Soils that would be indicative of wetlands are called hydric soils. Hydric-soil conditions have many different indicators and a lot of time (and numerous chapters in this book) would need to be spent discussing soil science to even begin to describe all of the properties. However, one of the indicators would be organic soils (Histosols) where either the upper 32 inches of the soil is at least 50 percent organic material or organic soil materials are directly overlying bedrock surfaces. Other indicators would be soils that exhibit saturated conditions for prolonged periods of time, such as staining from oxidized minerals, gleyed soils (soil horizons of gray color), sulfur (rotten egg) odors from hydrogen sulfide, and a high water content in the upper soil layers. There are many more indicators, but these provide some of the factors that field scientists look for when examining for wetland conditions.

Wetland hydrology occurs in areas that are either inundated or have saturated soils to land surface during parts of the growing season. The presence of water in a wetland environment should have a controlling influence on the types of plants and soils found in an area. The regularity and duration of saturation for an area will impact whether or not a wetland exists. For example, areas that are regularly or seasonally inundated or saturated for a certain percent of time during a growing season would be classified as having wetland hydrology, whereas areas irregularly or intermittently inundated or saturated would not fit this classification.

A number of tools are used by scientists to establish if an area has wetland hydrology. Many government agencies, such as the USGS, USACE, NRCS, and various State, County, and local agencies have information on streamflow, lake levels, flood hazard and flood control features, and other hydrology data that can aid in delineating wetland conditions. Aerial photographs, satellite images, and other remote sensing data also are useful in identifying areas of regular or prolonged saturation. Field data possibly is the most important piece of information, and this can consist of visual observation, watermarks on trees and rocks, drift lines, sediment deposits, and drainage patterns.

So, it is obvious that wetland delineation is a complex science involving biology, pedology (soil science), and hydrology. Understanding the complex ecosystems of wetlands, ranging from the microscopic life, through the many flora and fauna dependent on wetlands, to the larger animals such as migrating waterfowl and roaming mammals, is a topic requiring far greater coverage than can be covered in this chapter. Likewise, much more in-depth discussion of hydrology would be necessary to understand how wetlands act as points of recharge, discharge, and flow-through for watersheds. But hopefully this discussion provides the basics on how wetlands are defined and why they are important.

Chapter 33

Terminal Lakes

"Half a dozen little mountain brooks flow into Mono Lake, but not a stream of any kind flows out of it. It neither rises nor falls, apparently, and what it does with its surplus water is a dark and bloody mystery" (Twain, 1872).

The Basin and Range extending across Nevada and much of Utah contains many terminal lakes. A terminal lake is a body of water that has streams flowing into it but no streams flowing out of the lake. Inputs to a terminal lake also include direct precipitation to the lake and possibly ground water discharging to the lake.

Many of the lakes in Nevada, Utah, and eastern California are terminal lakes. For example, Mono Lake, the Great Salt Lake, Walker Lake, Pyramid Lake, Carson Sink, and numerous small lakes that occur in valleys in central and eastern Nevada are all terminal lakes.

Mono Lake, California. Photograph by M.S. Lico.

The reason the Basin and Range has so many terminal lakes is because of the topography. Basins typically are surrounded by high ridges that create conditions that allow water to collect in low areas and form lakes.

So, why doesn't the water continue to rise until it overflows the basins and spills into other areas? The reason is that, under natural conditions, terminal lakes typically are in a state of long-term equilibrium. The amount of inflow from streams, direct precipitation, and ground water is equal to the amount lost to evaporation. Over the course of a year, gains are made in the spring during snowmelt and rainfall, followed by losses in the summer due to evaporation, but from year to year, the lakes typically maintain somewhat steady levels.

However, over many years, if there are periods of sustained drought or continual wet years, terminal lake levels can fluctuate a great deal. Geologic evidence indicates that many of the terminal lakes in Nevada have both gone dry and have risen significantly in the past due to changes in the climate.

Terminal lakes can be described using the same equation we used for the water budget, where input equals output, plus or minus change in storage. In other words, the amount of water going into the lake as streams, precipitation, and ground-water flow equals the amount of water being evaporated off of the lake and being lost as ground water. And if the flow into the lake is different than the evaporation, there is a change in storage, or rather a rise or fall in the lake level.

As one can imagine, the streams and ground water that contribute to a terminal lake carry dissolved constituents (calcium, sodium, carbonate, chloride, etc.). When water evaporates, it leaves the dissolved constituents behind. Therefore, dissolved constituents in the lake waters become concentrated over time as more enter the lake and the water gets removed. This is why many terminal lakes are very salty and have a difficult time supporting certain aquatic life.

Many terminal lakes are at risk because of human influences on the water budget. By decreasing the amount of inflow into a lake, the water level of the lake will decline until either a new balance is reached (surface area of the lake declines until the evaporation is once again equal to the inflow) or the lake goes dry.

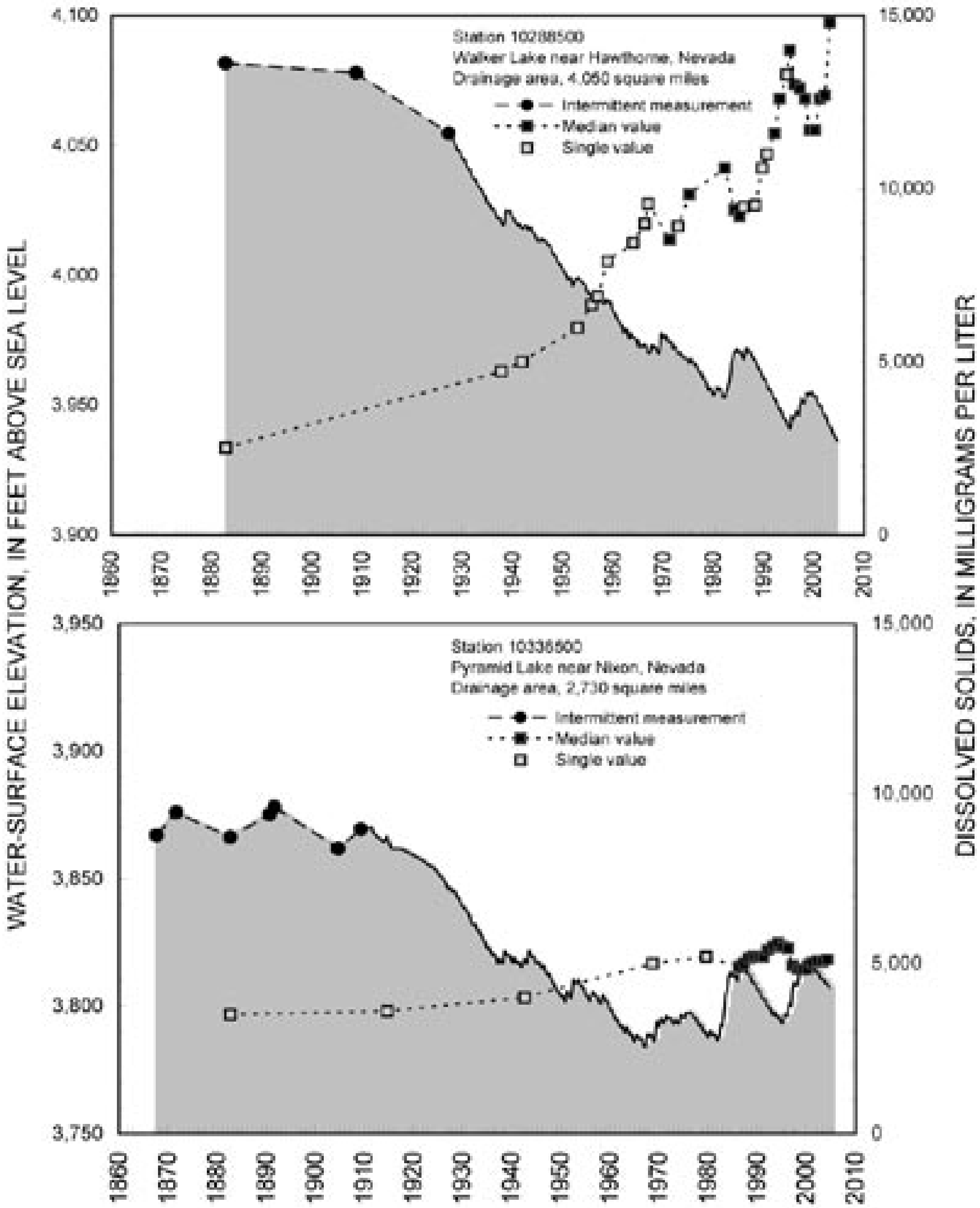
A good example of human impact on a terminal lake is again Mono Lake, California. Mono Lake is fed by streams, direct precipitation, and ground water, and losses are to evaporation. In 1941, when the lake was at a level of 6,410 feet above sea level, four of the five major streams feeding Mono Lake were diverted via the Los Angeles Aqueduct to southern California. The lake dropped to a level of 6,372 feet above sea level by 1981 (a drop of 38 feet over 40 years) and the surface area went from 53,500 acres in 1941 to about 40,000 acres in 1981 (Fetter, 1988). The salinity in the lake increased with the lowering of the lake level.

Terminal lakes in Nevada and Utah also are impacted by human influences. Water levels in many lakes have declined because of diversions of inflow to support agricultural and municipal needs. In many cases, diversions are limited and managed in order to maintain certain lake levels to support aquatic life, recreational activities, and salinity levels.

Walker Lake, north of Hawthorne, has been receding overall since the 1800s because of diversions of surface-water inflows and ground-water pumping in the watershed. USGS data illustrates that Walker Lake has declined about 143 feet between 1882 and 2003, which resulted in a steady rise in the dissolved solids in the lake. The concern for Walker Lake, as well as other desert terminal lakes, prompted Congress to approve $200 million in 2002 to address the issue. Presently, the BOR is examining the hydrology of desert terminal lakes and considering means to protect the lakes and their aquatic habitat from risk of continued water-level declines.

Pyramid Lake, north of Reno, is mainly fed by the Truckee River. Diversions of Truckee River water as part of the Newlands Project to support agriculture in western Nevada and withdrawals for municipal uses in the Reno area resulted in declines to Pyramid Lake. USGS data indicates that Pyramid Lake has declined about 58 feet between 1867 and 2003, with a similar associated rise in dissolved solids as seen in Walker Lake. These water-level declines greatly concerned the Pyramid Lake Paiute Tribe, who rely on the lake for food and resources, and other groups concerned with fishing, recreation, and other uses. Because of these concerns, flow and diversions in the Truckee River are now strongly regulated to insure adequate lake levels in Pyramid Lake.

Terminal lakes are an important part of the environment and history of the Basin and Range. They are a good example of how changes in one part of the water budget can affect the entire system.



Graph showing declining water levels in Pyramid and Walker Lakes.

Chapter 34

Floods

Floods make the news each year, and although control structures and dikes are built, as well as limiting building within flood plains, these disasters, along with major property damage and loss of life, still occur. It goes to show that nature will always be a force to be reckoned with regardless of our attempts to control our environment. But why do floods occur at all? This is because of many factors, some of which will be discussed in this chapter.

The National Flood Insurance Program defines a flood as, "A general and temporary condition of partial or complete inundation of two or more acres of normally dry land area or of two or more properties (at least one of which is your property) from:

- Overflow of inland or tidal waters,
- Unusual and rapid accumulation or runoff of surface waters from any source, or
- A mudflow.

[The] collapse or subsidence of land along the shore of a lake or similar body of water as a result of erosion or undermining caused by waves or currents of water exceeding anticipated cyclical levels that result in a flood." (Federal Emergency Management Agency, 2004).

That is a comprehensive definition that has a lot of good information. Most of the flooding we see inland in the U.S. is due to unusual and rapid accumulation or runoff of surface waters. Generally, flooding can occur if there is significant amounts of rainfall or snowmelt, or if the rainfall or snowmelt (or both) occur rapidly.

A process that scientists refer to as Horton Overland Flow (discussed in Chapter 5) relates to three steps that occur during precipitation or snowmelt. The first step is infiltration, where the water accumulating on the land surface infiltrates into the soils. The second step is when either the soils become saturated or the accumulation of rainfall/snowmelt exceeds the rate of infiltration into the soils and puddling occurs (filling of low areas). The third step is when puddles/depressions overfill and overland flow occurs. Excessive overland flow can contribute to flooding.

Obviously, many factors affect the occurrence of overland flow and flooding. The geology and soil types, land slope, vegetation cover, and depth to ground water are just some variables to consider. Another important variable is urbanization. Impervious land cover, such as streets and parking lots, do not allow infiltration of the precipitation and snowmelt. This water runs off these surfaces and drains into low areas or stormwater systems. Because of the limited infiltration in urban areas, much of the precipitation and snowmelt is channeled to the local streams, which can cause streams to overfill and flood. Plus, low areas such as underpasses and valleys can become flooded by the runoff.

The main meteorological factors related to the occurrence of flooding are quantity and duration of rain and snow during an event (how long it rains or snows), the intensity of precipitation (how heavy it rains or snows for a given period of time), the quantity of snowpack, and the speed of melting of snow pack. The following are some examples of how these factors have caused major flooding in the past.

Intensity of precipitation — In 1972, Rapid City, South Dakota, experienced a devastating flood that killed 238 people, injured 3,000 more people, and destroyed 1,335 homes, 5,000 cars, and 15 bridges. This happened because up to 15 inches of rain fell in the Black Hills to the west of Rapid City. The rain fell with such intensity that water rose as fast as 3.5 feet in 15 minutes in Rapid Creek and the peak flow in the creek was more than 50,000 cubic feet per second (more than 10 times the previous flood record).

What is most frightening is that the event happened over a short timeframe of little more than 7 hours, with rains beginning at 5 p.m. local and the flood cresting through downtown Rapid City at 12:15 a.m. By 5 a.m. that following morning, Rapid Creek was back within its banks. The setting for Rapid City is not that different from many of the cities and towns in Nevada.

QUANTITY AND DURATION OF PRECIPITATION — In 1993, the Mississippi River Basin in the Midwestern U.S. experienced a record flood that affected about 20 million acres of land in 9 states, resulted in 50 deaths, about 54,000 people evacuated, approximately 50,000 homes damaged or destroyed, 75 towns entirely flooded, and cost (in 1993 dollars) about $20 billion. Part of the cause for the flood was saturated soils (too saturated to absorb much more precipitation) in the upper Mississippi River Basin due to a wet fall in 1992 and a normal to above normal snow pack for the basin. Late March rains quickened snowmelt in the northern part of the basin, and persistent storms of high intensity and duration over the Midwest added large quantities of precipitation to the region. The Mississippi River at St. Louis rose above flood stage on April 8, then declined, rose again above flood stage on April 11, stayed above flood stage until May 24, then rose again above flood stage on June 27 and remained there until October 7 (146 days above flood stage).

QUANTITY OF SNOWPACK AND SPEED OF MELTING — The January 1997 flood of the Truckee, Carson, and Walker River Basins and the Lake Tahoe Basin impacted many people in western Nevada. The flood was triggered by above-normal snowpack during November and December for the Sierra Nevada, with an estimated water content for the snow pack at 150 to more than 200 percent of normal for late December and early January. In late December, a warm low-pressure system moved into the area and intense rainfall of up to 24 inches fell in some locations. Up to 80 percent of the snowpack in the lower elevations was melted by the rain, resulting in widespread runoff and record flooding. Millions of dollars in damage were estimated for each of the basins affected by the flooding.

Most recently, and maybe of most interest to local readers, is the flooding that has occurred in southern Utah, northwestern Arizona, and southern Nevada during the winter of 2004–05. Heavy rains in December and January resulted in some rivers reaching record flows. Floods damaged or destroyed several USGS gages along the Virgin and Muddy Rivers and on Beaver Dam and Meadow Valley washes. Preliminary estimates of the maximum (peak) discharge for the Virgin River near Littlefield, Arizona, are between 30,000 and 40,000 cubic feet per second, which, once the estimates are refined, may surpass the second-highest peak flow at this site of 35,000 cubic feet per second recorded in 1966. The highest flow for this site occurred in 1989 following the Quail Creek Dam failure, when 61,000 cubic feet per second was measured. Beaver Dam, near Enterprise, Utah, saw some very large flows, with peak stage (water level in the river) reaching 13.91 feet. This is more than 3.7 feet above the previous peak stage. USGS estimates of the peak discharge range from 8,000 to 10,000 cubic feet per second.

Flooding at Beaver Dam Wash, looking downstream. Photographs by D.A. Beck and R.J. Spaulding, USGS.

One can see that there are various factors that can result in flooding, and the degree of flooding and damage is strongly related to many meteorological, geological, and land-use conditions. Floods are a natural hazard that will always occur, but with improved capabilities to predict where and when floods will occur, along with better controls and land-use planning, the impacts from these events can be minimized.

Carson Valley during the 1997 flood. Photograph by P.A. Glancy.

Heavy flows in the Amargosa River, 2005. Photograph by B.J. Andraski, USGS.

Carson River during normal low flow (left) at about 55 cubic feet per second and at flood stage in January, 1997 at about 27, 500 cubic feet per second. Photograph on left by Rick Pruska. Photograph on right by Rhea Williams.

Chapter 35

Nevada Water Resources Association

Many people have asked where to obtain information about courses and workshops on water topics. A number of organizations offer such activities, but usually these activities are held in other parts of the country. Nevada is fortunate to have a local organization that offers conferences, workshops, seminars, and various publications on water. This organization is the Nevada Water Resources Association.

NWRA is a nonprofit, issue-neutral organization that is made up of a wide variety of water professionals, students, and non-scientists with an interest in water from across the State. What is meant by issue-neutral is that the group does not advocate any political or management position, but rather tries to provide information on the basic principles of water science, water law and policy, and water management with a focus on Nevada.

As pointed out on their web page, the mission of NWRA is to expand awareness of water issues throughout Nevada. Their purpose is to provide education, training, and networking (interaction between individuals) opportunities for people interested in understanding, developing, conserving, and protecting Nevada's water resources.

The group has a long history in Nevada, although the name has changed a bit over the years. Beginning as a group of Federal agencies called together by the State Engineer back in 1944 to discuss water issues, the group continued to meet annually to discuss working relationships and coordination. In 1951, the group became the Nevada Reclamation Association, and was affiliated with the National Reclamation Association. The group changed its name to the Nevada Water Resources Association in 1971. Today, NWRA consists of a wide variety of agencies, associations, and individuals with water interests and is independent of any ties to national organizations.

The organizational structure of NWRA consists of an executive director, the State Engineer, and 16 elected members of the Board of Trustees. These elected members represent 4 districts across Nevada, with 4 trustees for each district. The districts consist of District 1 (Clark, Lincoln, Nye, and Esmeralda Counties), District 2 (Mineral, Lyon, Douglas, Storey, and Churchill Counties and Carson City), District 3 (Lander, Eureka, Elko, and White Pine Counties) and District 4 (Humboldt, Pershing, and Washoe Counties).

Membership in NWRA is open to anyone with an interest in water issues. Presently, there are over 200 members and the roster has been growing each year. What started out as a group of Federal and State scientists, engineers, and water managers has grown into a diverse group, including lawyers, community planners, ranchers and farmers, politicians, environmentalists, developers, students, and many others with various interests. This mix of people brings together a broad range of viewpoints.

The major event for NWRA is the annual conference, which alternates each year between northern Nevada or southern Nevada (in 2004, it was held in Mesquite and in 2005, it was held in Reno). This is a 2–3 day conference that consists of technical presentations, discussion panels on current and on-going issues, workshops on educational topics, and general-interest talks. The conference also hosts student presentations and activities, information booths from various companies, the NWRA election of new board members, and many opportunities for interaction and networking.

NWRA hosts a number of symposiums and workshops throughout the year. For example, NWRA has recently offered workshops on water law and policy, arsenic contamination and remediation, surface-water modeling, ground-water basics, Lake Mead issues, Lake Tahoe issues, the hydrology of northeastern Nevada and the Ruby Mountains, and many other issues. NWRA offers seminars on many water topics, such as well construction, surface-water methods and analysis, and basic hydrology. Education for the general public and advanced training for water professionals is a main function for the organization.

The Journal of the Nevada Water Resources Association is a science publication that comes out twice a year (Spring and Fall) and offers articles on various technical subjects for water professionals. The journal is entirely on-line (available to everyone on the internet) and provides an outlet for publishing research focused on Nevada issues.

NWRA also offers other publications for sale on their web site. This is a good place to obtain materials of general and specific interest. For example, there are books on water law and water rights, which are topics many people have asked me about.

If you want more information about NWRA, you can contact the Executive Director at P.O. Box 8084, Reno, NV 89507 (775-626-6389) or check out the web site at http://www.nvwra.org.

Author's Note: Okay, my government disclaimer: I am writing about the NWRA as a public service and to identify a source of water information in Nevada. The USGS does not officially endorse or advocate membership in this or any other organization. Views expressed at NWRA functions and in their publications do not necessarily represent those of the USGS.

Panel discussion at the Annual NWRA conference.
Photograph by Donna Bloom, NWRA.

Chapter 36

The U.S. Geological Survey

The USGS was established by Congress over 125 years ago (March 3, 1879) with the objective of “classification of the public lands, and examination of the geological structure, mineral resources, and products of the national domain.” Our country was still quite new and much of it unexplored. The USGS had the task of surveying and documenting the topography, geology, and mineral resources of the U.S. and its territories to the West.

In reality, many of these activities were completed as various acts and efforts in the hundred years prior to the formation of the USGS. Congress was very interested in identifying lands that were classified as either mineral or nonmineral. Likewise, surveys of agricultural lands were important for influencing land sales and population migration to the West. In addition, topographic surveys and map construction were important efforts for establishing roadways and railroad routes.

In 1838, the Corps of Topographical Engineers was established to explore and map U.S. lands in North America. For over two decades, geologists worked with the Topographical Engineers in mapping and studying the West. During the 1850s, the Topographical Engineers explored four potential routes for the proposed transcontinental railroad. The importance of these surveys increased as mineral discoveries began to expand, such as gold in California in the late 1840s and gold in Colorado and silver in Nevada in 1859.

In 1867, Congress authorized western exploration in which geology would be the focus of the surveys. Four major surveys took place. One was lead by Clarence King (future first Director of the USGS) which explored the 40th parallel and went across Nevada. A second was lead by Ferdinand Hayden and was tasked with the survey of Nebraska (which, at that time, encompassed a huge area including the western Dakotas). He later was asked to survey the areas of Wyoming and Colorado. The third survey was John Wesley Powell’s exploration of the Rocky Mountains in Colorado and Utah and his subsequent trip through the canyons on the Colorado River. The fourth survey was the exploration of the country south and east of White Pine, Nevada, by Lieutenant George Wheeler. The purpose of this survey was to make a reconnaissance to the Colorado River for the establishment of wagon routes and military posts. (The USGS has a web site with photos from many of these surveys at <http://libraryphoto.er.usgs.gov>).

Following the Powell and Wheeler expeditions, plans for more thorough and systematic mapping of the territories were considered by Congress. Thus, the USGS was established and placed under the Department of the Interior.

A complete history of the USGS can be found at the USGS web site <http://pubs.usgs.gov/circ/c1050/> where much of this information was obtained. It is very interesting reading, and provides many more details than can be included in this short chapter.

Today, the USGS is a different organization than it was when first established. The USGS is made up of about 10,000 scientists, technicians, and support staff in about 400 offices in every State and in many other countries. Four major disciplines of research and data collection are within the USGS: Geology, Water Resources, Biological Resources, and Geography. Each of these has their own organizational structure, but provides expertise and interaction with other disciplines on various projects and efforts.

The mission of the USGS is to serve the Nation by providing reliable scientific information to (1) describe and understand the Earth; (2) minimize loss of life and property from natural disasters; (3) manage water, biological, energy, and mineral resources; and (4) enhance and protect our quality of life. The four major areas of focus for the USGS are natural hazards, resources, the environment, and information and data management.

It seems that many people associate the USGS with natural disasters, such as floods, earthquakes, and volcanoes. And rightfully so, because this is a part of our science that makes headlines and gets news coverage. The USGS is the organization that is there when these big events occur. Even movies quite often show the USGS on the scene of natural disasters.

Author's Note: My personal favorite is Dante's Peak, where Pierce Brosnan plays a USGS scientist who saves the day. Take my word for it, I look nothing like Pierce Brosnan and USGS vehicles are not equipped to drive through deep rivers, but the USGS does study volcanoes and earthquakes, as well as many other natural hazards.

Besides the study of natural hazards, the USGS has many other roles that may not be as dramatic, but are no less important. The USGS is the primary science agency for the Department of the Interior. This means that the USGS supplies scientific data, interpretation, and consultation to other Department of the Interior agencies, such as BLM, NPS, BOR, Bureau of Indian Affairs, Office of Surface Mining, and many others.

The USGS maintains a neutral, unbiased approach to scientific data collection, interpretation, and presentation. Across the country, USGS works in partnership with over 2,000 Federal, State, county, local, and Tribal agencies. Some USGS funds are allocated from Congress, but most of the budget is based on agencies that fund USGS research and data collection and on a Federal matching fund process where USGS uses allocated dollars to match funds from other agencies in order to partner in the science. These matching funds allow many State and local agencies to work with the USGS at a cost that is less of a burden to local resources.

One thing that sets the USGS apart from many other government agencies is that they are not a regulatory authority. In other words, they do not oversee or dictate how lands and natural resources are managed. They supply the data and scientific information for managers to make informed decisions, but are completely neutral on how those resources are managed.

Maintaining a neutral, unbiased standing on management issues for natural resources has allowed the USGS to be considered the authority in the field of earth sciences within the Federal Government. Their data and interpretations carry much weight in hearings and court cases concerning resource management because they look only at the science and are not influenced by outside pressures, political directions, or personal preferences. They have extensive quality assurance procedures to make sure the science is accurate and the interpretations remain neutral.

One of the strengths of the USGS is the ability to carry out large-scale, multidisciplinary investigations that increase the understanding of Earth and provide decision-makers with the tools and information they need to address issues of social concern. For example, since 1889, the USGS has maintained a nationwide streamgaging network that is used to assess streamflow at local, regional, and national scales. Presently, almost 7,000 gages are operated in cooperation with other agencies. The USGS has carried out many national programs, such as the Regional Aquifer System Analysis (RASA) and National Water Quality Assessment (NAWQA), both of which had large study units in Nevada.

Many of the topics discussed in previous chapters have addressed areas of research carried out by geologists in the Geologic Discipline. Geologic mapping of large areas and systematic mapping of 7.5-minute quadrangles across the country are completed by this group. Also, research that uses geophysics and the study of volcanoes, earthquakes, petroleum reserves, and many other areas of geologic sciences is conducted by the Geologic Discipline.

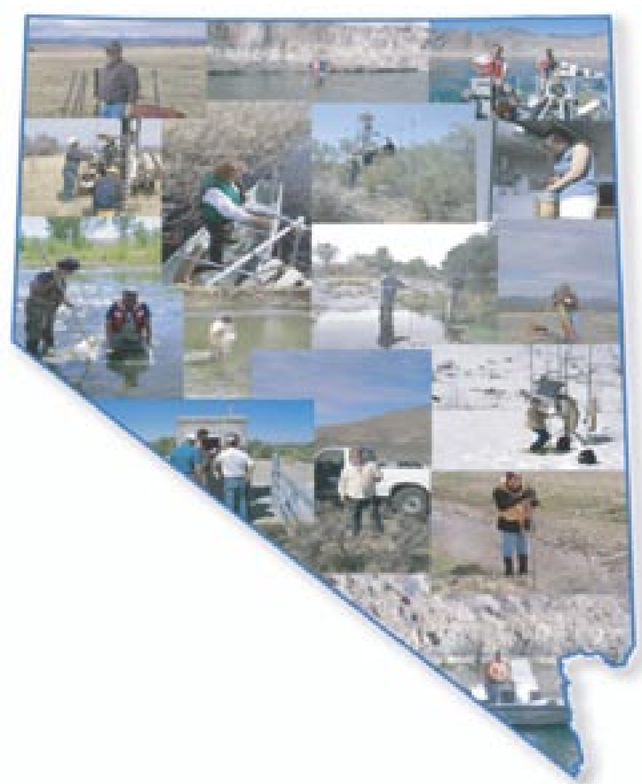
The Biological Resources Discipline of the USGS is a recent addition to our organization. Their focus is on the flora and fauna in our environment. Distribution of certain plant species, the documentation and occurrence of threatened and endangered plants and animals, migration patterns of large mammals, and the effects of human impacts on the biota are just some areas of study for the Biological Resources Discipline.

The Geography Discipline (previously called the National Mapping Program) is responsible for producing the topographic maps with which many people are familiar. The Geography Discipline also uses airplane imagery, satellite coverages, and space shuttle photos to document the complex surface of the Earth. Many investigative studies, such as land use changes over time and models for socioeconomic impacts based on population growth, also are performed by this group.

The largest discipline of the USGS is Water Resources. As mentioned earlier, this group conducts streamgaging across the country and carries out many large-scale studies. The Water Resources Discipline covers ground water, surface water, water quality, data management, and numerous focused specialties, such as geochemistry, geophysics, ET studies, GIS, and other areas. A Water Resources office is in each of the States, whereas the other three disciplines are mainly located in regional offices and science centers.

In Nevada, the USGS has a number of offices. The Nevada Water Science Center (where the State Representative for the USGS is located) is in Carson City. Water also has offices in Henderson (Las Vegas), which is shared with Biological Resources, and small offices in Elko and Mercury. Geology has a small office in Reno on the University of Nevada, Reno campus. Besides the shared space in Henderson, Biology also shares office space with USFWS and BLM in Reno.

Author's Note: The USGS is an outstanding organization and I am very proud to be part of this agency. Throughout college, while studying geology and hydrology, it was evident to me that most of the publications, numerical models, and earth science expertise were attributed to the USGS. As I saw it, the USGS was the earth science authority and I held the organization in such high esteem. When I was lucky enough to be offered a job, I was on cloud nine. And 17 years later, I am still as honored, proud, and humbled to be part of this organization as I was on my first day.



Chapter 37

References Cited

Alley, W.M., Reilly, T.E., and Franke, O.L., 1999, Sustainability of ground-water resources: U.S. Geological Survey Circular 1186, 79 p.

American Meteorological Society, 1959, Glossary of Meteorology: Huschke, R. E., ed., 638 p.

American Society of Civil Engineers, 2005, History and heritage, accessed March 25, 2005, at http://www.asce.org/history/resources.cfm?ProjectID=107&CategoryCode=11

Birkeland, P.W., 1984, Soils and geomorphology: Oxford University Press, 372 p.

Desert Research Institute, 2004, Western Regional Climate Center, accessed May 26, 2004, at http://www.wrcc.dri.edu/summary/mapnv.html

Federal Emergency Management Agency, 2004, Flood hazards, accessed January 11, 2004, at http://www.fema.gov/hazards/floods/

Federal Register, 1980, "40 CFR Part 230: Section 404(b)(1) Guidelines for specification of disposal sites for dredged or fill material": U.S. Government Printing Office, Washington, DC, v. 45, no. 249, p. 85352-85353.

———, 1982, "Title 33: Navigation and navigable waters; Chapter II, Regulatory programs of the Corps of Engineers": U.S. Government Printing Office, Washington, DC, v. 47, no. 138, p. 31810

Fetter, C.W., 1988, Applied Hydrogeology: Macmillan Publishing Co., New York, 592 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Prentice-Hall, Inc., Englewood Cliffs, NJ, 604 p.

Fremont, J.C., 1845, Report of the exploring expedition to the Rocky Mountains in the year 1842, and to Oregon and California in 1843–1844: Goles and Seaton, Washington DC.

Grayson, D.K., 1993, The desert's past—a natural prehistory of the Great Basin: Smithsonian Institution Press, Washington DC, 356 p.

Heath, R.C., 1989, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Horton, R.E., 1933, The role of infiltration in the hydrologic cycle: Transactions, American Geophysical Union, v. 14, p. 446-460.

———, 1940, An approach toward a physical interpretation of infiltration capacity: Soil Science Society of America, Proceedings, v. 4, p. 399-417.

Hoover Dam Bypass Project, 2005, accessed March 21, 2005 at http://www.hooverdambypass.org/default.htm

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., 2004, Estimated Use of Water in the United States in 2000: U.S. Geological Survey Circular 1268, 46 p.

Minnesota Board of Water and Soil Resources, 1996, Minnesota wetland delineation field guide: 229 p.

National Oceanic and Atmospheric Administration, 2005, Drought, accessed March 25, 2005, at http://www.wrh.noaa.gov/fgz/science/drought.php?wfo=fgz

National Park Service, 2001, Lake Mead National Recreation Area Strategic Plan 2001–2005: 72 p.

———, 2005, Lake Mead NRA, accessed March 11, 2005, at http://www.nps.gov/lame/learncultural.htm

Nevada Department of Conservation and Natural Resources, 2004, Department of Conservation and Natural Resources, accessed May 26, 2004, at http://dcnr.nv.gov/nrp01/climate.htm

Nevada Water Resources Association, 2004, NWRA, accessed December 22, 2004, at http://www.nvwra.org

Smith, J.L., Stone, J.C., Rowe, T.G., and Gardner, J.N., 1999, Selected hydrologic features of the Lake Tahoe Basin and surrounding area, California and Nevada, 1998: U.S. Geological Survey Water Resources Investigations Report 99-4031, 1 plate.

Southern Nevada Water Authority, 2005, Drought information, accessed March 25, 2005, at http://www.snwa.com/html/wr_drought.html.

———, 2005, Water use, accessed March 25, 2005, at http://www.snwa.com/html/ws_water_use_facts.html

———, 2005, 2005 Water Resource Plan: 50 p.

Southwest Hydrology, 2005, The Law of the River: Southwest Hydrology, vol. 4, no. 2, p. 19.

Twain, Mark, 1872, Roughing It: American Publishing Company

U.S. Army Corps of Engineers, 1987, Corps of Engineers wetlands delineation manual: Technical Report Y-87-11, 100 p., appendices.

U. S. Bureau of Reclamation, 2005, Hoover Dam, accessed March 17, 2005, at http://www.usbr.gov/lc/hooverdam/faqs/lakefaqs.html

U.S. Geological Survey, 2004, Lake Tahoe Data Clearinghouse, accessed March 25, 2005, at http://tahoe.usgs.gov/facts.html

———, U.S. Geological Survey, accessed December 29, 2004, at http://pubs.usgs.gov/circ/c1050/

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998, Ground water and surface water, a single resource: U.S. Geological Survey Circular 1139, 79 p.